

NPS ARCHIVE
1961
MURPHY, J.

SOLID STATE NEUTRON DETECTORS

JAMES F. MURPHY

DUDLEY KNOX LIBRARY
NAVAL POSTGRADUATE SCHOOL
MONTEREY CA 93943-5101

LIBRARY
U.S. NAVAL POSTGRADUATE SCHOOL
MONTEREY, CALIFORNIA

SOLID STATE NEUTRON DETECTORS

James F. Murphy
//
Lieutenant Commander
United States Navy
12 May 1961

Submitted in Partial Fulfillment of the Requirements for the Degree of
Master of Science, U. S. Naval Postgraduate School, Monterey, California

NPS Archive

1961

Murphy, J.

~~Thesis~~
M965

SOLID STATE NEUTRON DETECTORS

J. F. Murphy

ABSTRACT

Two methods of fabricating neutron detectors have been developed utilizing the principles of the solid state ionized particle detector. The (n,α) reactions of Li^6 and B^{10} are used for slow neutron detection. The Lithium and Boron are used as diffusants, for P and N type Silicon respectively, to create p-n junction diode detectors with efficiencies of the order of 1%. The fission of U^{235} is used for the detection of both slow and fast neutrons. The U^{235} is vacuum coated onto surface barrier detectors. Efficiencies of .004% have been obtained from these units in a thermal beam from the Livermore 2 MW pool-type reactor.

THE UNIVERSITY OF CHICAGO
LIBRARY

The University of Chicago Library
has received a donation of
the following books from
the University of Chicago
Library. The books are
the property of the
University of Chicago
Library and are not to be
loaned or sold without
the permission of the
University of Chicago
Library. The books are
the property of the
University of Chicago
Library and are not to be
loaned or sold without
the permission of the
University of Chicago
Library.

SOLID STATE NEUTRON DETECTORS

CONTENTS

	<u>Page No.</u>
I. Introduction	1
II. General Theory	2
1. Crystalline Structure	2
2. Band Structure	3
3. Fermi Levels	3
4. Surface Barrier Junctions	5
5. PN Junctions	9
6. Detection of Ionized Particles	11
7. Neutron Detection	15
(a) Elastic Reactions	15
(b) Inelastic Reactions	15
III. Preparation of Detectors	19
1. Crystals	19
2. Surface Barrier Detectors	24
3. Diffused PN Detectors	25
IV. Experimental Units and Results	28
1. Uranium Detectors	28
(a) Preparation of Experimental Units	28
(b) Results	29
2. B^{10} Detectors	31
(a) Preparation of Experimental Units	31
(b) Results	31
3. Li^6 Detectors	
(a) Preparation of Experimental Units	32
(b) Results	32

THE HISTORY OF THE COUNTY OF MIDDLESEX

1	OF THE NAME OF THE COUNTY	1
2	OF THE BOUNDARIES OF THE COUNTY	2
3	OF THE DIVISION OF THE COUNTY INTO PARISHES	3
4	OF THE TOWNS AND VILLAGES OF THE COUNTY	4
5	OF THE RIVERS AND STREAMS OF THE COUNTY	5
6	OF THE LAKES AND POND OF THE COUNTY	6
7	OF THE FORESTS OF THE COUNTY	7
8	OF THE MINES OF THE COUNTY	8
9	OF THE MANUFACTURES OF THE COUNTY	9
10	OF THE MILLS OF THE COUNTY	10
11	OF THE BRIDGES OF THE COUNTY	11
12	OF THE TOWNSHIP OF ST. MARTIN	12
13	OF THE TOWNSHIP OF ST. MARTIN	13
14	OF THE TOWNSHIP OF ST. MARTIN	14
15	OF THE TOWNSHIP OF ST. MARTIN	15
16	OF THE TOWNSHIP OF ST. MARTIN	16
17	OF THE TOWNSHIP OF ST. MARTIN	17
18	OF THE TOWNSHIP OF ST. MARTIN	18
19	OF THE TOWNSHIP OF ST. MARTIN	19
20	OF THE TOWNSHIP OF ST. MARTIN	20
21	OF THE TOWNSHIP OF ST. MARTIN	21
22	OF THE TOWNSHIP OF ST. MARTIN	22
23	OF THE TOWNSHIP OF ST. MARTIN	23
24	OF THE TOWNSHIP OF ST. MARTIN	24
25	OF THE TOWNSHIP OF ST. MARTIN	25
26	OF THE TOWNSHIP OF ST. MARTIN	26
27	OF THE TOWNSHIP OF ST. MARTIN	27
28	OF THE TOWNSHIP OF ST. MARTIN	28
29	OF THE TOWNSHIP OF ST. MARTIN	29
30	OF THE TOWNSHIP OF ST. MARTIN	30
31	OF THE TOWNSHIP OF ST. MARTIN	31
32	OF THE TOWNSHIP OF ST. MARTIN	32
33	OF THE TOWNSHIP OF ST. MARTIN	33
34	OF THE TOWNSHIP OF ST. MARTIN	34
35	OF THE TOWNSHIP OF ST. MARTIN	35
36	OF THE TOWNSHIP OF ST. MARTIN	36
37	OF THE TOWNSHIP OF ST. MARTIN	37
38	OF THE TOWNSHIP OF ST. MARTIN	38
39	OF THE TOWNSHIP OF ST. MARTIN	39
40	OF THE TOWNSHIP OF ST. MARTIN	40
41	OF THE TOWNSHIP OF ST. MARTIN	41
42	OF THE TOWNSHIP OF ST. MARTIN	42
43	OF THE TOWNSHIP OF ST. MARTIN	43
44	OF THE TOWNSHIP OF ST. MARTIN	44
45	OF THE TOWNSHIP OF ST. MARTIN	45
46	OF THE TOWNSHIP OF ST. MARTIN	46
47	OF THE TOWNSHIP OF ST. MARTIN	47
48	OF THE TOWNSHIP OF ST. MARTIN	48
49	OF THE TOWNSHIP OF ST. MARTIN	49
50	OF THE TOWNSHIP OF ST. MARTIN	50
51	OF THE TOWNSHIP OF ST. MARTIN	51
52	OF THE TOWNSHIP OF ST. MARTIN	52
53	OF THE TOWNSHIP OF ST. MARTIN	53
54	OF THE TOWNSHIP OF ST. MARTIN	54
55	OF THE TOWNSHIP OF ST. MARTIN	55
56	OF THE TOWNSHIP OF ST. MARTIN	56
57	OF THE TOWNSHIP OF ST. MARTIN	57
58	OF THE TOWNSHIP OF ST. MARTIN	58
59	OF THE TOWNSHIP OF ST. MARTIN	59
60	OF THE TOWNSHIP OF ST. MARTIN	60
61	OF THE TOWNSHIP OF ST. MARTIN	61
62	OF THE TOWNSHIP OF ST. MARTIN	62
63	OF THE TOWNSHIP OF ST. MARTIN	63
64	OF THE TOWNSHIP OF ST. MARTIN	64
65	OF THE TOWNSHIP OF ST. MARTIN	65
66	OF THE TOWNSHIP OF ST. MARTIN	66
67	OF THE TOWNSHIP OF ST. MARTIN	67
68	OF THE TOWNSHIP OF ST. MARTIN	68
69	OF THE TOWNSHIP OF ST. MARTIN	69
70	OF THE TOWNSHIP OF ST. MARTIN	70
71	OF THE TOWNSHIP OF ST. MARTIN	71
72	OF THE TOWNSHIP OF ST. MARTIN	72
73	OF THE TOWNSHIP OF ST. MARTIN	73
74	OF THE TOWNSHIP OF ST. MARTIN	74
75	OF THE TOWNSHIP OF ST. MARTIN	75
76	OF THE TOWNSHIP OF ST. MARTIN	76
77	OF THE TOWNSHIP OF ST. MARTIN	77
78	OF THE TOWNSHIP OF ST. MARTIN	78
79	OF THE TOWNSHIP OF ST. MARTIN	79
80	OF THE TOWNSHIP OF ST. MARTIN	80
81	OF THE TOWNSHIP OF ST. MARTIN	81
82	OF THE TOWNSHIP OF ST. MARTIN	82
83	OF THE TOWNSHIP OF ST. MARTIN	83
84	OF THE TOWNSHIP OF ST. MARTIN	84
85	OF THE TOWNSHIP OF ST. MARTIN	85
86	OF THE TOWNSHIP OF ST. MARTIN	86
87	OF THE TOWNSHIP OF ST. MARTIN	87
88	OF THE TOWNSHIP OF ST. MARTIN	88
89	OF THE TOWNSHIP OF ST. MARTIN	89
90	OF THE TOWNSHIP OF ST. MARTIN	90
91	OF THE TOWNSHIP OF ST. MARTIN	91
92	OF THE TOWNSHIP OF ST. MARTIN	92
93	OF THE TOWNSHIP OF ST. MARTIN	93
94	OF THE TOWNSHIP OF ST. MARTIN	94
95	OF THE TOWNSHIP OF ST. MARTIN	95
96	OF THE TOWNSHIP OF ST. MARTIN	96
97	OF THE TOWNSHIP OF ST. MARTIN	97
98	OF THE TOWNSHIP OF ST. MARTIN	98
99	OF THE TOWNSHIP OF ST. MARTIN	99
100	OF THE TOWNSHIP OF ST. MARTIN	100

V. Electronics	33
VI. Conclusions	34
Acknowledgements	35
Bibliography	36
Appendix A	37
Appendix B	42

ILLUSTRATIONS

- Fig. 1. Metal and N type semiconductor showing the relative position of the Fermi levels for the case $\phi_m > \phi_s$.
- Fig. 2. Metal and N type semiconductor joined to produce a barrier of height $\phi_m - \phi_s$.
- Fig. 3. Metal to N type semiconductor ohmic contact.
- Fig. 4. P-N Junction
- Fig. 5. Uranium evaporation jig.
- Fig. 6. Filament detail.
- Fig. 7. Vacuum chamber.
- Fig. 8. Flow diagram of basic fabrication operations.
- Fig. 9. Silicon single crystal, silicon slices and quartz holder.
- Fig. 10. Mounted silicon detector.
- Fig. 11. Diffusion furnace.
- Fig. 12. Uranium-235 alpha spectrum.
- Fig. 13. Uranium-235 fission fragment spectrum.
- Fig. 14. Diode characteristics of the uranium coated, oxide surface barrier detector.
- Fig. 15. Diode characteristics of the uranium coated, freshly etched surface barrier detector.
- Fig. 16. Diode characteristics of the uranium coated, boron diffused detector.
- Fig. 17. Diode characteristics of the uranium and gold coated surface barrier detector.
- Fig. 18. Diode characteristics of a boron-10 painted, boron diffused detector.
- Fig. 19. Diode characteristics of a boron-10 diffused detector.
- Fig. 20. Boron-10 reaction particle spectrum, 0 volts reverse bias.
- Fig. 21. Boron-10 reaction particle spectrum, 5 volts reverse bias.

- Fig. 22. Boron-10 reaction particle spectrum, 10 volts reverse bias.
- Fig. 23. Lithium-6 reaction particle spectrum, 20 volts reverse bias.
- Fig. 24. Electronics test equipment.

I. INTRODUCTION

The development of ionized particle detectors has received considerable attention during the past few years.¹⁻⁶ At the present time it is known that the Chalk River Laboratory,⁷ the Lewis Research Center⁸ and the Westinghouse Electric Corporation⁹ are experimenting with ionized particle detectors which have been coated with neutron sensitive elements. This paper is concerned with the use of Li^6 and B^{10} as diffusants to directly form silicon p-n junction neutron detectors and the use of uranium to form surface barrier neutron detectors.

Natural occurring lithium, an interstitial donor, has recently been used by Elliott⁶ to form a p-n junction and to extend the depletion region with an ion drift process. A similar process for the separated isotope Li^6 is discussed in the present paper. In this case neutron detection is accomplished with a $\text{Li}^6 (n, \alpha) \text{T}$ reaction converting captured neutrons into charged particles, which in turn are detected within the depletion region. P-n junctions were also directly formed by a shallow diffusion of B^{10} (90-92% enriched) in N-type silicon. Here the $\text{B}^{10} (n, \alpha) \text{Li}^7$ reaction formed ionized particles for neutron detection.

Additionally, neutron detection was investigated using the fission process in U^{238} and U^{235} for the conversion of fast and slow neutrons. In this case the restricted range of the highly ionized fission fragments required the use of surface barrier junction to detect the product charged particles. This was accomplished by vacuum coating uranium onto preformed gold surface barrier silicon diodes.

Attempts were also made to form uranium surface barriers directly on silicon.

II. GENERAL THEORY

1. Crystalline Structure.

All solids may be classified as crystals or non-crystals. A crystal is a structure which is produced by the repetition of a basic unit due to translation and is characterized by its extreme regularity. If this regularity or periodicity extends throughout the entire piece of material it is said to be a "single crystal". If the piece of material is an agglomerate of smaller crystallites, it is said to be "polycrystalline". In a non-crystal the atoms or atom groups are present in an irregular or random fashion. Examples of this type are super-cooled liquids, glasses and plastics (plastics sometimes exhibit a repetition of a basic unit but it is a spiral type structure, not translatable).

Crystals may be divided into seven crystal systems, fourteen space lattices, two hundred and thirty space groups and an infinite number of crystal structures. A complete discussion of these systems may be found in any basic solid state physics text.¹⁰

Silicon is an insulator with a valence of four. Like germanium it has a diamond structure in which each cell is composed of 8 atoms and each atom has 4 nearest neighbors. Strong bonds between the atoms result from a sharing or mutual exchange of electrons with its nearest neighbors. This type of binding is particularly stable and is called "covalent binding". This binding is of an electrostatic nature but can be explained only on a quantum mechanical basis utilizing what is known as exchange interaction.

THE UNIVERSITY OF CHICAGO PRESS
CHICAGO, ILL.

THE UNIVERSITY OF CHICAGO PRESS

CHICAGO, ILL.

THE UNIVERSITY OF CHICAGO PRESS

CHICAGO, ILL.

THE UNIVERSITY OF CHICAGO PRESS

CHICAGO, ILL.

THE UNIVERSITY OF CHICAGO PRESS

CHICAGO, ILL.

THE UNIVERSITY OF CHICAGO PRESS

CHICAGO, ILL.

THE UNIVERSITY OF CHICAGO PRESS

CHICAGO, ILL.

THE UNIVERSITY OF CHICAGO PRESS

CHICAGO, ILL.

THE UNIVERSITY OF CHICAGO PRESS

CHICAGO, ILL.

THE UNIVERSITY OF CHICAGO PRESS

CHICAGO, ILL.

THE UNIVERSITY OF CHICAGO PRESS

CHICAGO, ILL.

THE UNIVERSITY OF CHICAGO PRESS

CHICAGO, ILL.

2. Band Structure

The complete theory on band structure is contained in any basic atomic physics text. Quantum mechanically the electron energy levels are determined by the quantum numbers. In a collection of atoms of the same type, the electron energy levels will separate into bands of energy levels. These bands have energy widths characteristics of the solid, but the number of levels within the band is determined only by the number of atoms present. N atoms provide N levels within each band. However, each level can accommodate two electrons because of spin. Therefore, a collection of N atoms lead to $2N$ states within each band. In silicon and certain other diamond structures, there is a quantum mechanically forbidden zone between the valence and conduction bands. The conduction band is the lowest unfilled band at 0°K . The valence band is the next lower band. Metals contain an overlapping of bands so that no forbidden zone exists at these higher energy levels. In silicon this forbidden zone or gap occurs between the $3s$ and $3p$ shells and has an energy span of 1.11 eV . In germanium the gap energy is $.72\text{ eV}$ and it occurs between the $4s$ and $4p$ shells. Diamond on the other hand has a comparatively large gap energy, 6 eV , and it is located between the $2s$ and $2p$ shells.

3. Fermi Levels

The location of the Fermi level determines the type of silicon (i.e. Intrinsic (I), Donor (N), or Acceptor (P)).

Intrinsic silicon contains no impurities. At 0°K there will be no electrons in the conduction band while the valence band will be full.

At any elevated temperature some states in the conduction band will be occupied by electrons while an equal number of vacant states will exist in the valence band. It can be shown that since the number of electrons in the conduction band and the number of vacant states in the valence band are a function of the Fermi probability function, there is a virtual Fermi face midway between the two bands.¹¹

If a group V contaminant is introduced, the atoms of which are substituted for silicon atoms, there will exist one very loosely bound electron for each atom substituted. Only four of the contaminant's five valence electrons are required to complete the bonding with the silicon. To preserve charge neutrality the fifth electron must orbit the parent nucleus. The radius of the orbit is extended by the dielectric constant of the silicon. Since this fifth electron is loosely bound, it is easily excited into the conduction band of the silicon leaving the parent nucleus ionized. This process provides an excess number of electrons in the conduction band thus the Fermi probability function and consequently the Fermi face is shifted in the direction of the conduction band. Silicon containing a group V contaminant is called "donor" or "N" type.

If a group III contaminant is introduced substitutionally into silicon, there is a deficit of one bonding electron for each atom substituted. The vacant bond or hole can be thought of as an orbiting positive charge. Thermal excitation will fill this hole with a silicon valence electron thus transferring the hole to a silicon neighbor. The process of filling and transferring gives mobility to the hole.

The first difficulty arises from the fact that the
 quantity of the good is not constant, but varies with the
 price. This is the case of most goods, and it is this
 fact which makes the problem of the consumer more
 difficult. The consumer must choose between different
 quantities of the good, and the quantity chosen will
 depend on the price of the good.

The second difficulty arises from the fact that the
 quantity of the good is not constant, but varies with the
 price. This is the case of most goods, and it is this
 fact which makes the problem of the consumer more
 difficult. The consumer must choose between different
 quantities of the good, and the quantity chosen will
 depend on the price of the good. The third difficulty
 arises from the fact that the quantity of the good is
 not constant, but varies with the price. This is the
 case of most goods, and it is this fact which makes
 the problem of the consumer more difficult. The
 consumer must choose between different quantities of
 the good, and the quantity chosen will depend on the
 price of the good. The fourth difficulty arises from
 the fact that the quantity of the good is not constant,
 but varies with the price. This is the case of most
 goods, and it is this fact which makes the problem
 of the consumer more difficult. The consumer must
 choose between different quantities of the good, and
 the quantity chosen will depend on the price of the
 good.

The fifth difficulty arises from the fact that the
 quantity of the good is not constant, but varies with
 the price. This is the case of most goods, and it is
 this fact which makes the problem of the consumer
 more difficult. The consumer must choose between
 different quantities of the good, and the quantity
 chosen will depend on the price of the good. The
 sixth difficulty arises from the fact that the quantity
 of the good is not constant, but varies with the
 price. This is the case of most goods, and it is this
 fact which makes the problem of the consumer more
 difficult. The consumer must choose between different
 quantities of the good, and the quantity chosen will
 depend on the price of the good.

The group III contaminant thus provides more holes in the valence band than there are electrons in the conduction band. The Fermi probability function and consequently the Fermi face resultantly shift in the direction of the valence band. In taking on the extra electron the contaminant takes on a negative charge. Silicon containing a group III contaminant is called "acceptor" or "P" type.

4. Surface Barrier Junction

In a metal the atoms are held together with what is known as a "Metallic Bond". It can be thought of as a structure formed by positively charged metal ions embedded in a sea of mobile free electrons. In spite of the fact that the electrons move freely from atom to atom, charge neutrality is preserved. The Fermi level lies at the upper edge of the electron distribution within the partially filled valence band. If by some mechanism additional electrons are introduced into the valence band, the Fermi level will be raised and the metal will take on a net negative charge. This charge will appear as an infinitesimally thin sheet of charge on the surface of the metal. If, on the other hand, electrons are somehow drained from the valence band, the Fermi level is lowered and the metal takes on a net positive charge. This charge also appears as a thin sheet on the surface. In a semiconductor the situation is somewhat similar. In N type material the electrons in the conduction band are present as a result of excitations from the valence band and from ionization of the donor impurities. If the electrons are somehow drained from the conduction band, the Fermi level will be lowered and the semiconductor will take on a net positive charge. Unlike the metal, the charge in this case will be a distributed positive charge made up of the ionized donor atoms. Figure 1 shows

a metal and an N type semiconductor side by side, but not touching. In this case the work function (ϕ_m) of the metal is larger than the work function (ϕ_s) of the semiconductor. When the two are brought into contact, Figure 2, electrons will drain from the conduction band of the semiconductor and will be injected into the valence band of the metal until the two Fermi levels are at the same energy. The metal now has a thin negative surface charge while the semiconductor has a distributed positive charge or "Space Charge Region". An electric field is set up which is located entirely within the space charge region of the semiconductor. The height of the resulting potential barrier corresponds to the difference of the two work functions.

The current flow across the barrier is described in detail in the literature.^{10,11} The total current is made up of four components, the electron flow from the metal to the semiconductor (I_a), the electron flow from the semiconductor to the metal (I_b), the hole flow from the metal to the semiconductor (I_c), and the hole flow from the semiconductor to the metal (I_d). See Figure 2. In equilibrium, an energy $q(\phi_m - \phi_s)$ must be supplied to the electrons to enable them to cross the potential barrier.

Then $I_a = -I_b = Ae^{-q(\phi_m - \phi_s)/kT}$. The holes must be supplied energy in the amount of $q\psi$ in order to cross the barrier. Then $I_c = -I_d = Be^{-q\psi/kT}$.

Under small forward and reverse voltage bias, the current components I_a and I_d will remain the same as for equilibrium conditions because the potential barrier they see does not change. However, the potential barrier as seen by components I_b and I_c does change. When a bias voltage (V_b) is applied the Fermi level in the semiconductor is raised

or lowered depending on whether a forward or reverse bias is applied. The amount of energy necessary to be supplied to I_b electrons and I_c holes, under forward bias in order to cross the barrier, is reduced by the amount qV_b , from the equilibrium condition. Under reverse bias the opposite is true. When the Fermi level is raised under forward bias, it means that less electrons will be drained from the conduction band, hence less donors will be ionized and the space charge region will be narrower (Equation A-10). Conversely the space charge region will be increased under a reverse bias. In equation A-12 it is noted that the expression for capacitance is the same as for a parallel plate capacitor. In a parallel plate capacitor the capacitance varies directly with the area of the plates and inversely with the separation between them, while the charge appears as a thin sheet of charge on each plate. In a metal to semiconductor contact there is a thin sheet of charge on the metal but on the other plate which is the semiconductor there is a distributed space charge. Applying a reverse bias increases the width of the space charge region thus increasing the effective plate separation hence, decreasing the capacitance. The only other method of decreasing the capacitance is to physically reduce the area of the contact. The reduction of capacitance is important in detectors since the pulse height of the output pulse is inversely proportional to the capacitance.

By evaporating a thin coating of a metal onto N type silicon, assuming ϕ_m is greater than ϕ_s , a rectifying contact is made which under reverse bias becomes a detector for ionized particles.

When applying leads to a semiconductor device care must be taken

or a rectifying junction will occur where it is not desired. To obtain an ohmic (non-rectifying) junction between a metal and a semiconductor, the metal must be chosen such that its work function is smaller than that of the N type semiconductor. In this case the Fermi levels must once again line up. To accomplish this, electrons are drained from the valence band of the metal lowering its Fermi level. These electrons are injected into the conduction band of the semiconductor raising its Fermi level. Since there are many unoccupied states in the conduction band of the semiconductor there is no opposition to the flow of electrons in either direction, and there is no potential barrier set up. (Figure 3)

The analysis of the metal to P type semiconductor contact is similar to the one just carried out for the metal to N type semiconductor. To obtain a rectifying contact between a metal and P type semiconductor the metal must be chosen such that its work function is smaller than that of the semiconductor. To obtain an ohmic contact the work function of the metal must be greater than that of the semiconductor.

The solution of Poisson's equation for the case of the metal to semiconductor contact is contained in Appendix A. The charge distribution arises from the fact that there exists an abrupt change from high conductivity material to high resistivity material.

5. PN Junctions

The contact between two semiconductors of opposite type behave similar to that between a metal and a semiconductor. The Fermi level of the two semiconductors must again line up. To accomplish this electrons will drain from the N type semiconductor and be injected into the conduction band of the P type material. Holes will drain from the valence band of the P type semiconductor and be injected into the valence band of the N type material. This process equalizes the Fermi levels and creates a space charge region on both sides of the contact. The space charge region is composed of ionized donors and negatively charged acceptors in the N and P material respectively (Figure 4).

The current is again composed of four components and is described in detail in the literature.^{12,13} I_a is the flow of electrons from the P to the N type semiconductor. I_b is the flow of electrons from the N to the P type semiconductor. I_c is the flow of holes from the P to the N type semiconductor and I_d is the flow of holes from the N to the P type semiconductor. In equilibrium, $I_a = -I_b = Ae^{-q\psi/kT}$, and $I_c = -I_d = Be^{-q\psi/kT}$. A and B are constant only for a constant temperature and they can be determined by solving the continuity equation and applying Fermi statistics¹¹.

$$A = \frac{qD_n}{\sqrt{D_n \tau_n}} \cdot \frac{2(2\pi m k T)^{3/2}}{(h^2)}$$

$$B = \frac{qD_p}{\sqrt{D_p \tau_p}} \cdot \frac{2(2\pi m^* k T)^{3/2}}{(h^2)}$$

the first part of the paper, we shall consider the case in which

the function $f(x)$ is continuous and the function $g(x)$ is continuous.

Let us suppose that the function $f(x)$ is continuous and the function

$g(x)$ is continuous. Then the function $f(x)$ is continuous and the function

$g(x)$ is continuous. Then the function $f(x)$ is continuous and the function

$g(x)$ is continuous. Then the function $f(x)$ is continuous and the function

$g(x)$ is continuous. Then the function $f(x)$ is continuous and the function

$g(x)$ is continuous. Then the function $f(x)$ is continuous and the function

$g(x)$ is continuous. Then the function $f(x)$ is continuous and the function

$g(x)$ is continuous. Then the function $f(x)$ is continuous and the function

$g(x)$ is continuous. Then the function $f(x)$ is continuous and the function

$g(x)$ is continuous. Then the function $f(x)$ is continuous and the function

$g(x)$ is continuous. Then the function $f(x)$ is continuous and the function

$g(x)$ is continuous. Then the function $f(x)$ is continuous and the function

$g(x)$ is continuous. Then the function $f(x)$ is continuous and the function

$g(x)$ is continuous. Then the function $f(x)$ is continuous and the function

$g(x)$ is continuous. Then the function $f(x)$ is continuous and the function

$g(x)$ is continuous. Then the function $f(x)$ is continuous and the function

$g(x)$ is continuous. Then the function $f(x)$ is continuous and the function

$g(x)$ is continuous. Then the function $f(x)$ is continuous and the function

$g(x)$ is continuous. Then the function $f(x)$ is continuous and the function

$$\frac{f(x)}{g(x)} = \frac{f(x)}{g(x)}$$

$$\frac{f(x)}{g(x)} = \frac{f(x)}{g(x)}$$

q = Electronic charge

D_n = Diffusion constant for electrons

D_p = Diffusion constant for holes

t_n = Minority carrier lifetime for electrons
in P type material

t_p = Minority carriers lifetime for holes
in N type material

m = Mass of the electron

m^* = Effective mass of the hole

k = Boltzmann's constant

h = Plank's constant

T = Temperature in degrees Kelvin

Under reverse bias I_b and I_c reduce to almost zero.

The total current flow then is the sum of I_a and I_d which is called the "saturation current". The sum of the widths of the two space charge regions, called the "Depletion region", is increased under reverse bias, equation B-2, and the capacitance is decreased, equation B-3. The charge distribution for this type of symmetrical junction is a graded distribution which may be approximated by a straight line. For the solution of Poisson's equation for a graded type junction see Appendix B. This symmetrical junction can be attained, practically, only in grown type junctions, where the concentration of dopants can be controlled so there is equal doping on both sides of the junction.

For diffused type junctions an extremely high concentration of dopant is located on one side of the junction and the contaminant distribution approaches a step function. As a result, the electric field and the depletion region are located mostly within the lightly doped side.

6. Detection of Ionized Particles

Energetic charged particles passing through a solid produce hole-electron pairs through interactions with the solid's electrons. These electrons, even from deep lying occupied bands, may be excited into unoccupied higher energy bands. The maximum energy that may be transferred to these electrons is $E_{\max} = \frac{4mME}{(m+M)} \approx \frac{4mE}{M}$ where m is the mass of the electron and M and E are the mass and energy of the charged particles. For a 4 Mev alpha or a 1 Mev proton this is approximately 2 Kev of energy. On the average only 3.5 ev of energy is expended to produce an electron-hole pair in silicon.^{2,13} It takes on the order of 10^{-12} sec for the excited electrons to seek the lowest lying unoccupied band (conduction band) and for the holes to seek the highest occupied band (valence band). The hole and electron will then combine to complete the de-excitation with a characteristic time known as the "carrier lifetime". If these electron-hole pairs are produced within the depletion region they are rapidly swept aside and collected owing to the action of the electric field therein. If the electron-hole pairs are produced outside of the depletion region but within a diffusion length (L), they will probably diffuse into the depletion region and be collected. Diffusion length (L) is defined as $L = \sqrt{Dt}$, where D is the diffusion constant for holes or electrons as the case may be and t is the carrier lifetime. Electron-hole pairs created more than a diffusion length from the depletion region will recombine with their characteristic lifetime and not contribute to the output pulse.

THEORY OF THE EARTH'S CRUST

The theory of the earth's crust is a branch of geology which deals with the structure and composition of the uppermost layer of the earth. It is a subject of great importance, as it is the basis of all geological knowledge. The theory of the earth's crust is based on the study of the rocks which form the crust, and on the study of the forces which have acted upon them. The theory of the earth's crust is a branch of geology which deals with the structure and composition of the uppermost layer of the earth. It is a subject of great importance, as it is the basis of all geological knowledge. The theory of the earth's crust is based on the study of the rocks which form the crust, and on the study of the forces which have acted upon them.

Within the depletion region the clouds of electrons and holes pass each other so rapidly, owing to the action of the electric field, that very little recombination can take place. If however, certain impurities or crystal defects are present, trapping or recombination centers may be set up. A trapping center is a center in which a carrier may be temporarily trapped and then re-emitted. Carriers re-emitted from a trapping center cause a tail to form on the current pulse. A recombination center is a center in which a carrier may also be temporarily trapped but prior to re-emission a carrier of the opposite type is also trapped, in which case, the two carriers recombine. Recombination centers cause a degradation of the current pulse since less charges will be collected. The contribution of each carrier to the total charge is derived as follows:

$$m \frac{dv}{dt} = q \mathcal{E} \quad \text{or} \quad mv \frac{dv}{dt} = \frac{dE}{dt} = qv \mathcal{E} .$$

$\frac{dE}{dt}$ is the rate at which the electric field gives energy to the carrier, and q , v , and m are charge, velocity and mass of the carrier. This energy comes from the junction capacitor which has $\frac{Q^2}{2C}$ of energy stored.

Thus

$$\frac{dE}{dt} = \frac{d}{dt} \left(\frac{Q^2}{2C} \right) = \frac{Qi}{C} = V_c i = qv \mathcal{E}$$

V_c is the total voltage across the capacitor. Then

$$i = \frac{dQ}{dt} = \frac{qv}{V_c} \mathcal{E} = \frac{q}{V_c} \quad \frac{dx}{dt} \frac{dV}{dx} = \frac{q}{V_c} \frac{dV}{dt} .$$

$\frac{dV}{dt}$ is the rate of change of the potential at the location of the carrier due to the carrier drift in the electric field. Finally

$$\int dQ = Q_{\text{eff}} = \frac{q}{V_c} \int dV = \frac{q \Delta V}{V_c}$$

where Q_{eff} is the effective charge at the electrodes due to the motion of one carrier through the fraction $\frac{\Delta V}{V_c}$ of the total potential on the capacitor. Thus it can be seen that one carrier will contribute one charge q on making a complete passage across the capacitor. An electron-hole pair created between the plates of the capacitor will still only contribute one charge q since each carrier will contribute a fraction of the charge. The total charge (Q) is equal to $Q_{\text{eff}} N$, where N is the number of hole-electron pairs liberated by a particle whose energy is E . If E is in Mev then

$$Q = \frac{Q_{\text{eff}} E}{3.5} \times 10^6 \text{ coulombs} \quad (1)$$

The charge collected is some fraction of the total charge available, because some of the hole-electron pairs are created more than a diffusion length from the depletion region while others are lost due to recombination within recombination centers.

The current pulse produced by the collection of the hole-electron pairs will have a rise time which is the carrier transit time (t_t) across the depletion region.

$$t_t = \frac{d}{v_d} = \frac{d}{\mu} \mathcal{E}$$

d is the width of the depletion region, v_d is the carrier drift velocity and μ is the carrier mobility. These carrier transit times are typically of the order of nanoseconds. The carrier mobilities are functions of the impurity concentration and temperature. Typical values for mobility at room temperature for high resistivity silicon is $\mu_n = 450 \text{ cm}^2/\text{volt-sec}$ and $\mu_e = 1200 \text{ cm}^2/\text{volt-sec}$. Curves of electron and hole mobilities as functions of the impurity concentration may be found in reference¹⁴.

...the ... of the ...

...the ... of the ...

...the ... of the ...

...the ... of the ...

...the ... of the ...

...the ... of the ...

...the ... of the ...

...the ... of the ...

...the ... of the ...

...the ... of the ...

...the ... of the ...

...the ... of the ...

...the ... of the ...

...the ... of the ...

...the ... of the ...

...the ... of the ...

...the ... of the ...

...the ... of the ...

...the ... of the ...

...the ... of the ...

...the ... of the ...

...the ... of the ...

...the ... of the ...

...the ... of the ...

...the ... of the ...

...the ... of the ...

...the ... of the ...

...the ... of the ...

...the ... of the ...

The ideal solid state detector should have rapid charge collection with an accompanying low loss of carriers. Rapid charge collection is attained through use of high resistivity material. High resistivity material has high carrier mobilities and in addition is capable of supporting large electric fields. The low loss of carriers is attained by having wide depletion regions which originate at the surface and freedom from recombination centers.

The first part of the paper is devoted to a general discussion of the problem of the origin of life. It is shown that the problem is not only a scientific one, but also a philosophical one. The second part of the paper is devoted to a detailed discussion of the problem of the origin of life. It is shown that the problem is not only a scientific one, but also a philosophical one. The third part of the paper is devoted to a detailed discussion of the problem of the origin of life. It is shown that the problem is not only a scientific one, but also a philosophical one.

The fourth part of the paper is devoted to a detailed discussion of the problem of the origin of life. It is shown that the problem is not only a scientific one, but also a philosophical one. The fifth part of the paper is devoted to a detailed discussion of the problem of the origin of life. It is shown that the problem is not only a scientific one, but also a philosophical one. The sixth part of the paper is devoted to a detailed discussion of the problem of the origin of life. It is shown that the problem is not only a scientific one, but also a philosophical one. The seventh part of the paper is devoted to a detailed discussion of the problem of the origin of life. It is shown that the problem is not only a scientific one, but also a philosophical one. The eighth part of the paper is devoted to a detailed discussion of the problem of the origin of life. It is shown that the problem is not only a scientific one, but also a philosophical one. The ninth part of the paper is devoted to a detailed discussion of the problem of the origin of life. It is shown that the problem is not only a scientific one, but also a philosophical one. The tenth part of the paper is devoted to a detailed discussion of the problem of the origin of life. It is shown that the problem is not only a scientific one, but also a philosophical one.

7. Neutron Detection

Neutrons, possessing no charge, can be detected only through secondary elastic or inelastic reactions.

a. Elastic Reactions

Elastic collisions between fast neutrons and a hydrogenous material produce recoil protons. These protons can then be detected in the manner described in the previous section. Fast neutron detection devices might thus be fabricated merely by encapsulating the detector in plastic. No investigations were made using recoil proton counters. It is mentioned here in the interest of presenting a complete picture of possible solid state neutron detection devices.

b. Inelastic Reactions

Vacuum coating p-n or surface barrier detectors with fissionable material presents a means of detection of both slow and fast neutrons. The fragments resulting from fission are highly ionized and possess high kinetic energies. These fragments are detectable as described in Section II-6, producing very large pulses.

Uranium was used as the fissionable material in this investigation. It was desired to check previous work where uranium was coated on preformed p-n junction detectors^{7,8} and to compare these units with uranium coated surface barrier detectors.

As a first approximation the energy of the incident neutron may be neglected since the reaction energy for uranium is approximately 200 Mev. In this case the laboratory coordinate system will coincide with the center of mass coordinate system. The average mass of the two fission fragments of U^{235} are 97 and 139 amu.¹⁶

THE JOURNAL OF THE

ROYAL ANTHROPOLOGICAL INSTITUTE OF GREAT BRITAIN AND IRELAND

VOLUME LXXV. PART I. 1905.

LONDON: PUBLISHED BY THE INSTITUTE.

PRINTED BY THE INSTITUTE, 21, BEDFORD SQUARE, W.C.

THE JOURNAL OF THE ROYAL ANTHROPOLOGICAL INSTITUTE OF GREAT BRITAIN AND IRELAND

VOLUME LXXV. PART I. 1905.

LONDON: PUBLISHED BY THE INSTITUTE.

PRINTED BY THE INSTITUTE, 21, BEDFORD SQUARE, W.C.

THE JOURNAL OF THE ROYAL ANTHROPOLOGICAL INSTITUTE OF GREAT BRITAIN AND IRELAND

VOLUME LXXV. PART I. 1905.

LONDON: PUBLISHED BY THE INSTITUTE.

PRINTED BY THE INSTITUTE, 21, BEDFORD SQUARE, W.C.

THE JOURNAL OF THE ROYAL ANTHROPOLOGICAL INSTITUTE OF GREAT BRITAIN AND IRELAND

VOLUME LXXV. PART I. 1905.

LONDON: PUBLISHED BY THE INSTITUTE.

PRINTED BY THE INSTITUTE, 21, BEDFORD SQUARE, W.C.

THE JOURNAL OF THE ROYAL ANTHROPOLOGICAL INSTITUTE OF GREAT BRITAIN AND IRELAND

VOLUME LXXV. PART I. 1905.

LONDON: PUBLISHED BY THE INSTITUTE.

PRINTED BY THE INSTITUTE, 21, BEDFORD SQUARE, W.C.

THE JOURNAL OF THE ROYAL ANTHROPOLOGICAL INSTITUTE OF GREAT BRITAIN AND IRELAND

VOLUME LXXV. PART I. 1905.

LONDON: PUBLISHED BY THE INSTITUTE.

PRINTED BY THE INSTITUTE, 21, BEDFORD SQUARE, W.C.

THE JOURNAL OF THE ROYAL ANTHROPOLOGICAL INSTITUTE OF GREAT BRITAIN AND IRELAND

VOLUME LXXV. PART I. 1905.

$$T_L = \frac{M_H}{M_L + M_H} R = \frac{139}{236} 200 = 118 \text{ Mev}$$

$$T_H = \frac{M_L}{M_L + M_H} R = 82 \text{ Mev}$$

where T_L and M_L are the kinetic energy and mass of the light fragment and T_H and M_H are the kinetic energy and mass of the heavy fragment.

Many fissionable materials will not fission with slow neutrons. The neutron energy at which they commence to fission is called the "threshold energy". Some examples are¹⁷.

Isotope	Threshold Energy (Mev)	Cross Section at 2 Mev (Barns)
90 Th ²³²	1.3	.11
91 Pa ²³¹	.5	1.05
92 U ²³⁵	0	1.32
92 U ²³⁶	1.0	.8
92 U ²³⁸	1.0	.53
94 Pu ²³⁹	0	2.0

If it is desired to detect only fast neutrons, one of the isotopes with a high threshold energy could be used for the detector coating. One difficulty arises from the fact that isotope separation is difficult for these high mass elements. A better method would be to use enriched U²³⁵ for the detector coating and to use an absorber to selectively filter out the slow neutrons.

Slow neutrons may be detected by using (n,α) or (n,p) reactions. In general these are exoergic reactions. To determine the total charge which may be obtained equation 1 must be modified to include the reaction energy (R).

$$\lim_{n \rightarrow \infty} \frac{1}{n} \sum_{k=1}^n f\left(\frac{k}{n}\right) = \int_0^1 f(x) dx$$

$$\lim_{n \rightarrow \infty} \frac{1}{n} \sum_{k=1}^n f\left(\frac{k}{n}\right) = \int_0^1 f(x) dx$$

Consider the function $f(x) = x^2$ on the interval $[0, 1]$. The Riemann sum approximation of the integral $\int_0^1 x^2 dx$ using n subintervals is given by $\frac{1}{n} \sum_{k=1}^n \left(\frac{k}{n}\right)^2$. The error in this approximation is bounded by $\frac{1}{6n^2}$. Therefore, as n increases, the approximation becomes more accurate.

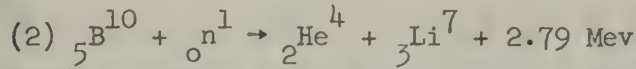
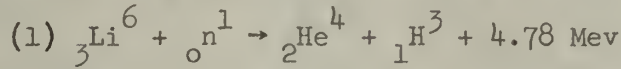
n	$\frac{1}{n} \sum_{k=1}^n \left(\frac{k}{n}\right)^2$	Error
10	0.385	$\frac{1}{600}$
20	0.390	$\frac{1}{2400}$
30	0.393	$\frac{1}{5400}$
40	0.395	$\frac{1}{9600}$
50	0.397	$\frac{1}{15000}$
60	0.398	$\frac{1}{21600}$

The table shows that as n increases, the Riemann sum approximation of the integral $\int_0^1 x^2 dx$ approaches the exact value of $\frac{1}{3}$. The error decreases as n increases, confirming that the Riemann sum is a valid method for approximating definite integrals. The error term $\frac{1}{6n^2}$ provides a quantitative measure of the accuracy of the approximation.

$$Q_T = \frac{Q_{\text{eff}} (E_n + R) \times 10^6}{3.5} \text{ coulombs} \quad (2)$$

where R is in Mev.

The two reactions used in this investigation are:



Both Li^6 and B^{10} can be used as impurity diffusants to fabricate solid state neutron detectors. Lithium is a group I element. It acts as a donor since it diffuses interstitially. Boron is a group three acceptor.

The average thermal neutron energy (E_n) is .025 ev. As a first approximation E_n can be neglected since $E_n \ll R$.

$$Q_T \approx \frac{Q_{\text{eff}} R \times 10^6}{3.5} \text{ coulombs} \quad (3)$$

Since E_n is neglected the laboratory coordinate system again coincides with the center of mass coordinate system. The kinetic energies of the reaction particles are:

$$T_1 = \frac{M_2}{M_1 + M_2} R \quad (4)$$

$$T_2 = \frac{M_1}{M_1 + M_2} R \quad (5)$$

T_1 and M_1 are the kinetic energy and mass of the first reaction particle. T_2 and M_2 are the kinetic energy and mass of the second reaction particle. For reaction (1) and (2) the reaction particle energies are

(9)

$$\lim_{n \rightarrow \infty} \frac{f_n(x)}{f(x)} = 1$$

for all x in \mathbb{R} .

Let $f_n(x) = \frac{1}{n} \sum_{k=0}^{n-1} f(x + k/n)$.

$$\lim_{n \rightarrow \infty} f_n(x) = f(x) \quad (1)$$

$$\lim_{n \rightarrow \infty} \frac{f_n(x)}{f(x)} = 1 \quad (2)$$

Let $f(x) = \sin(x)$. Then $f_n(x) = \frac{1}{n} \sum_{k=0}^{n-1} \sin(x + k/n)$.
Let $f(x) = \cos(x)$. Then $f_n(x) = \frac{1}{n} \sum_{k=0}^{n-1} \cos(x + k/n)$.
Let $f(x) = e^x$. Then $f_n(x) = \frac{1}{n} \sum_{k=0}^{n-1} e^{x + k/n}$.

Let $f(x) = \frac{1}{x}$. Then $f_n(x) = \frac{1}{n} \sum_{k=0}^{n-1} \frac{1}{x + k/n}$.
Let $f(x) = \ln(x)$. Then $f_n(x) = \frac{1}{n} \sum_{k=0}^{n-1} \ln(x + k/n)$.

(10)

$$\lim_{n \rightarrow \infty} \frac{f_n(x)}{f(x)} = 1$$

for all x in \mathbb{R} .

Let $f_n(x) = \frac{1}{n} \sum_{k=0}^{n-1} f(x + k/n)$.
Let $f(x) = \sin(x)$. Then $f_n(x) = \frac{1}{n} \sum_{k=0}^{n-1} \sin(x + k/n)$.

(11)

$$\lim_{n \rightarrow \infty} \frac{f_n(x)}{f(x)} = 1$$

(12)

$$\lim_{n \rightarrow \infty} \frac{f_n(x)}{f(x)} = 1$$

Let $f(x) = \sin(x)$. Then $f_n(x) = \frac{1}{n} \sum_{k=0}^{n-1} \sin(x + k/n)$.
Let $f(x) = \cos(x)$. Then $f_n(x) = \frac{1}{n} \sum_{k=0}^{n-1} \cos(x + k/n)$.
Let $f(x) = e^x$. Then $f_n(x) = \frac{1}{n} \sum_{k=0}^{n-1} e^{x + k/n}$.
Let $f(x) = \frac{1}{x}$. Then $f_n(x) = \frac{1}{n} \sum_{k=0}^{n-1} \frac{1}{x + k/n}$.
Let $f(x) = \ln(x)$. Then $f_n(x) = \frac{1}{n} \sum_{k=0}^{n-1} \ln(x + k/n)$.

Reaction	Particle	Kinetic Energy (Mev)
(1)	${}^4_2\text{He}$	2.05
(1)	${}^3_1\text{He}$	2.73
(2)	${}^4_2\text{He}$	1.78
(2)	${}^7_3\text{Li}$	1.01

The total charge (Q_T) is independent of the angle of incidence of the neutron since the kinetic energy of the reaction particles is due almost entirely to the reaction energy (R).

Page 100

Page 101

Page 102

100

101

102

103

104

105

106

107

108

109

110

111

The first part of the book is devoted to a general introduction to the subject of the book. The second part is devoted to a detailed discussion of the various aspects of the subject. The third part is devoted to a discussion of the various methods of solving the problem. The fourth part is devoted to a discussion of the various applications of the theory. The fifth part is devoted to a discussion of the various extensions of the theory. The sixth part is devoted to a discussion of the various generalizations of the theory. The seventh part is devoted to a discussion of the various specializations of the theory. The eighth part is devoted to a discussion of the various modifications of the theory. The ninth part is devoted to a discussion of the various improvements of the theory. The tenth part is devoted to a discussion of the various refinements of the theory. The eleventh part is devoted to a discussion of the various enhancements of the theory. The twelfth part is devoted to a discussion of the various optimizations of the theory. The thirteenth part is devoted to a discussion of the various upgrades of the theory. The fourteenth part is devoted to a discussion of the various updates of the theory. The fifteenth part is devoted to a discussion of the various revisions of the theory. The sixteenth part is devoted to a discussion of the various corrections of the theory. The seventeenth part is devoted to a discussion of the various amendments of the theory. The eighteenth part is devoted to a discussion of the various supplements of the theory. The nineteenth part is devoted to a discussion of the various additions of the theory. The twentieth part is devoted to a discussion of the various deletions of the theory. The twenty-first part is devoted to a discussion of the various insertions of the theory. The twenty-second part is devoted to a discussion of the various replacements of the theory. The twenty-third part is devoted to a discussion of the various substitutions of the theory. The twenty-fourth part is devoted to a discussion of the various transpositions of the theory. The twenty-fifth part is devoted to a discussion of the various rotations of the theory. The twenty-sixth part is devoted to a discussion of the various reflections of the theory. The twenty-seventh part is devoted to a discussion of the various translations of the theory. The twenty-eighth part is devoted to a discussion of the various dilations of the theory. The twenty-ninth part is devoted to a discussion of the various contractions of the theory. The thirtieth part is devoted to a discussion of the various expansions of the theory. The thirty-first part is devoted to a discussion of the various compressions of the theory. The thirty-second part is devoted to a discussion of the various stretches of the theory. The thirty-third part is devoted to a discussion of the various squeezes of the theory. The thirty-fourth part is devoted to a discussion of the various pulls of the theory. The thirty-fifth part is devoted to a discussion of the various pushes of the theory. The thirty-sixth part is devoted to a discussion of the various drags of the theory. The thirty-seventh part is devoted to a discussion of the various drops of the theory. The thirty-eighth part is devoted to a discussion of the various lifts of the theory. The thirty-ninth part is devoted to a discussion of the various moves of the theory. The fortieth part is devoted to a discussion of the various shifts of the theory. The forty-first part is devoted to a discussion of the various slides of the theory. The forty-second part is devoted to a discussion of the various turns of the theory. The forty-third part is devoted to a discussion of the various flips of the theory. The forty-fourth part is devoted to a discussion of the various folds of the theory. The forty-fifth part is devoted to a discussion of the various bends of the theory. The forty-sixth part is devoted to a discussion of the various twists of the theory. The forty-seventh part is devoted to a discussion of the various turns of the theory. The forty-eighth part is devoted to a discussion of the various rotations of the theory. The forty-ninth part is devoted to a discussion of the various translations of the theory. The fiftieth part is devoted to a discussion of the various dilations of the theory. The fifty-first part is devoted to a discussion of the various contractions of the theory. The fifty-second part is devoted to a discussion of the various expansions of the theory. The fifty-third part is devoted to a discussion of the various compressions of the theory. The fifty-fourth part is devoted to a discussion of the various stretches of the theory. The fifty-fifth part is devoted to a discussion of the various squeezes of the theory. The fifty-sixth part is devoted to a discussion of the various pulls of the theory. The fifty-seventh part is devoted to a discussion of the various pushes of the theory. The fifty-eighth part is devoted to a discussion of the various drags of the theory. The fifty-ninth part is devoted to a discussion of the various drops of the theory. The sixtieth part is devoted to a discussion of the various lifts of the theory. The sixty-first part is devoted to a discussion of the various moves of the theory. The sixty-second part is devoted to a discussion of the various shifts of the theory. The sixty-third part is devoted to a discussion of the various slides of the theory. The sixty-fourth part is devoted to a discussion of the various turns of the theory. The sixty-fifth part is devoted to a discussion of the various flips of the theory. The sixty-sixth part is devoted to a discussion of the various folds of the theory. The sixty-seventh part is devoted to a discussion of the various bends of the theory. The sixty-eighth part is devoted to a discussion of the various twists of the theory. The sixty-ninth part is devoted to a discussion of the various turns of the theory. The seventieth part is devoted to a discussion of the various rotations of the theory. The seventy-first part is devoted to a discussion of the various translations of the theory. The seventy-second part is devoted to a discussion of the various dilations of the theory. The seventy-third part is devoted to a discussion of the various contractions of the theory. The seventy-fourth part is devoted to a discussion of the various expansions of the theory. The seventy-fifth part is devoted to a discussion of the various compressions of the theory. The seventy-sixth part is devoted to a discussion of the various stretches of the theory. The seventy-seventh part is devoted to a discussion of the various squeezes of the theory. The seventy-eighth part is devoted to a discussion of the various pulls of the theory. The seventy-ninth part is devoted to a discussion of the various pushes of the theory. The eightieth part is devoted to a discussion of the various drags of the theory. The eighty-first part is devoted to a discussion of the various drops of the theory. The eighty-second part is devoted to a discussion of the various lifts of the theory. The eighty-third part is devoted to a discussion of the various moves of the theory. The eighty-fourth part is devoted to a discussion of the various shifts of the theory. The eighty-fifth part is devoted to a discussion of the various slides of the theory. The eighty-sixth part is devoted to a discussion of the various turns of the theory. The eighty-seventh part is devoted to a discussion of the various flips of the theory. The eighty-eighth part is devoted to a discussion of the various folds of the theory. The eighty-ninth part is devoted to a discussion of the various bends of the theory. The ninetieth part is devoted to a discussion of the various twists of the theory. The ninety-first part is devoted to a discussion of the various turns of the theory. The ninety-second part is devoted to a discussion of the various rotations of the theory. The ninety-third part is devoted to a discussion of the various translations of the theory. The ninety-fourth part is devoted to a discussion of the various dilations of the theory. The ninety-fifth part is devoted to a discussion of the various contractions of the theory. The ninety-sixth part is devoted to a discussion of the various expansions of the theory. The ninety-seventh part is devoted to a discussion of the various compressions of the theory. The ninety-eighth part is devoted to a discussion of the various stretches of the theory. The ninety-ninth part is devoted to a discussion of the various squeezes of the theory. The hundredth part is devoted to a discussion of the various pulls of the theory.

III. Preparation of Detectors

1. Crystals

Diode preparation requires several mechanical operations common to both surface barrier and p-n types. See Figure 8. In all operations the utmost cleanliness must be observed because any contamination may ruin the detector. Between each operation the silicon must be thoroughly cleaned using only ultra high purity chemicals. A degreaser such as trichlorethylene should be used followed by an alcohol rinse followed by several rinses in distilled and deionized water. Handle the silicon only with clean tweezers to eliminate possible contamination with the hands.

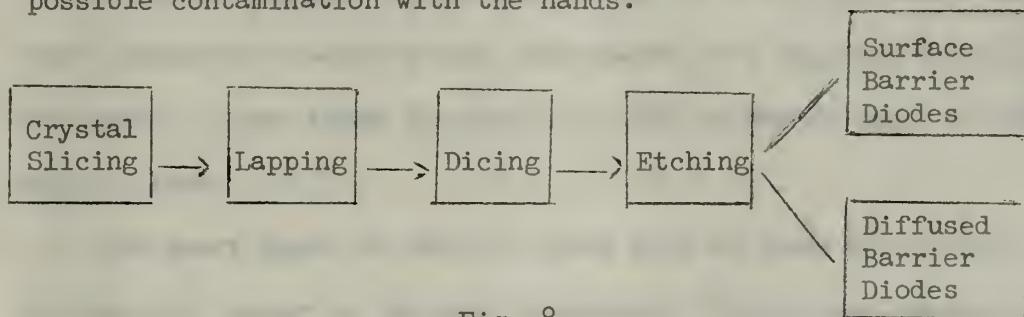


Fig. 8

Several silicon single crystals were purchased from the Merck Chemical Company. They are cylindrical in shape with diameters of approximately 20 mm and of various lengths between three and four inches. These crystals are high purity and thus high resistivity with resistivities ranging between 100 and 4000 ohm-cm of both N and P types.

Silicon is hard, brittle and chips easily. For this reason a high speed diamond saw must be used for slicing the crystal into circular discs (Fig. 9). The thickness of the disc is largely dependent upon the ultimate use of the detector (i.e. A d/dx detector must be thin so very little of the detected particles energy is lost in passing through the silicon.) If it is desired to use the

detector in a spectrometer, all of the detected particle's energy must be expended within the silicon and thus a fairly thick disc must be used. If it is desired to merely detect, almost any thickness may be used. A thickness of .030 inches was arbitrarily settled upon. Approximately .015 inches will be removed in subsequent operations.

During the slicing operation the silicon crystal must be held perfectly rigid. To do this the crystal is glued to a rectangular slab of porcelain using a resin pitch. The resin pitch was selected because it has good adhesive qualities, melts at a low temperature and is easily removed with alcohol (Fig. 9). The porcelain slab is then clamped in a metal holder and placed in a magnetic vice on the saw bench. A saw blade thickness of .020 inches is used to minimize silicon loss.

The scarf marks of the saw blade must be removed or uneven etching will occur in the next operation. These scarf marks are removed in a lapping process similar to that used for grinding glass.¹⁷ A lucite mask containing six circular holes is placed between two stainless steel lapping blocks. The function of the mask is to contain the silicon slices, force the slices to slide over the lower lapping block and act as a limit so too much silicon will not be ground off. The upper block is driven by an eccentric mounted in the chuck of a slow speed drill press at 16 rpm. At this speed approximately .002 inches of silicon are removed per hour. A mixture of John Crane 1900 or 1950 lapping compound and water is used for the grinding compound. Stainless steel was used as the material for the lapping blocks since the water in the grinding compound would

THE first of the two main branches of the ...
... the ...
... the ...
... the ...

THE second of the two main branches of the ...
... the ...
... the ...
... the ...

THE third of the two main branches of the ...
... the ...
... the ...
... the ...

THE fourth of the two main branches of the ...
... the ...
... the ...
... the ...

rust cast iron. Both faces of the silicon are lapped at the same time. The upper block (5" in diameter), driven by the eccentric, rotates against a lip on the mask (6" in diameter) thus forcing the mask, containing the silicon, to slide over the surface of the lower block (7" in diameter), which is stationary. A mask thickness of .020 inches was used. When the silicon slices are ground to a thickness of .020 inches, the mask, being the same thickness and relatively soft, inhibits further grinding. In this manner also, the two faces of the silicon discs are maintained very close to parallel.

Upon completion of lapping the silicon slices are diced to their final size. This size is determined by the amount of capacitance the ultimate system can tolerate and still get a good signal to noise ratio. Since the expression for capacitance is the same as that of a parallel plate capacitor eq. A-12, the capacitance varies directly with the first power of the area. As a result the smaller the area the smaller the capacitance and the larger the voltage signal. Most of the slices were diced into squares .200 inches on a side. To do this the silicon slices are once again mounted on the porcelain slab with the resin pitch but this time they are mounted in horizontal stacks to facilitate cutting.

The dicing operation may be deferred until after the diffusion operation. If it is, there exists the possibility of damaging the diffused surface due to increased handling but the sides will be free of the diffusant. If the dicing takes place at this point, any diffusion operation will also diffuse into the sides. This diffusant, however, may be removed by hand lapping or etching.

and the other two, the first of which is the most important, are the two most important of the three.

The first of these is the most important, and the second is the most important of the two.

The second of these is the most important, and the third is the most important of the two.

The third of these is the most important, and the fourth is the most important of the two.

The fourth of these is the most important, and the fifth is the most important of the two.

The fifth of these is the most important, and the sixth is the most important of the two.

The sixth of these is the most important, and the seventh is the most important of the two.

The seventh of these is the most important, and the eighth is the most important of the two.

The eighth of these is the most important, and the ninth is the most important of the two.

The ninth of these is the most important, and the tenth is the most important of the two.

The tenth of these is the most important, and the eleventh is the most important of the two.

The eleventh of these is the most important, and the twelfth is the most important of the two.

The twelfth of these is the most important, and the thirteenth is the most important of the two.

The thirteenth of these is the most important, and the fourteenth is the most important of the two.

The fourteenth of these is the most important, and the fifteenth is the most important of the two.

The fifteenth of these is the most important, and the sixteenth is the most important of the two.

The sixteenth of these is the most important, and the seventeenth is the most important of the two.

The seventeenth of these is the most important, and the eighteenth is the most important of the two.

The eighteenth of these is the most important, and the nineteenth is the most important of the two.

The nineteenth of these is the most important, and the twentieth is the most important of the two.

The twentieth of these is the most important, and the twenty-first is the most important of the two.

The twenty-first of these is the most important, and the twenty-second is the most important of the two.

Etching is a chemical means of polishing the silicon surface. The purpose is to expose any possible dislocations or other crystal-line imperfections, which would render the crystal useless. It also provides a smooth boundary from which diffusion can take place. To protect the reverse side during the etching process a mask of picein wax, dissolved in trichlorethylene, is applied. The volatile portions are then removed by placing the sample under an infrared lamp for 2 to 3 minutes. This leaves a hard wax coating which the acid will not attack and which is easily removed by again dissolving with trichlorethylene. The etch solution is a modified form of the standard CP-4 solution which contains:

	Parts by Volume
Concentrated Nitric Acid (70%)	3
Hydroflouric Acid (48%)	1
Glacial Acetic Acid	1

The nitric acid oxidizes the exposed silicon surface. The oxide formed is then removed by the action of the hydroflouric acid.

This reaction is fast ~~therefore~~ a buffering agent, the glacial acetic acid, must be used to make the reaction controllable. Dearnley and Whitehead⁴ also recommend cooling the etch solution in an ice water bath as a further means of controlling the reaction.

During the etching process small bubbles form on the surface of the silicon. If they are not removed uneven etching will occur. These bubbles may be removed by agitating the silicon samples or by bubbling nitrogen gas through the etch solution. The latter is recommended.

Upon completion of etching the silicon must not be immediately exposed to air as this produces a brown discoloration on the silicon. Instead the etch solution must be diluted and decanted several

times before removal of the silicon to a beaker of distilled and deionized water where it is washed by diluting and decanting. The silicon is then dried by placing it in a stream of dry nitrogen gas. The silicon samples sometimes float to the surface of the etch solution where they become discolored. To avoid this the reverse side of the silicon should be attached to a piece of teflon or polyethylene, using the picein wax. The teflon or polyethylene will then act as an anchor to hold the samples below the surface. A fresh batch of etchant will produce a mirror finish in 4 to 5 minutes. An aged batch may take somewhat longer.

2. Surface Barrier Detectors

Surface barrier diodes are generally made from N type silicon because the difference between the thermionic work functions of most metals and that of silicon is generally greater for N type than it is for P type. This means that by using N type silicon for a base, larger barriers will be produced resulting also in a wider space charge regions. Care must be taken to ensure that the work function of the metal is **greater** than that of the N type silicon. If the work function of the metal is smaller than that of the N type silicon, an ohmic contact is made. The opposite holds true for the case of P type silicon.

For N type silicon a surface oxide layer provides an excellent barrier. After the etching process, the silicon sample is placed in a wet atmosphere for several hours, preferably over night, to form the barrier. After removal of the mask and a thorough cleaning the diodes are mounted. See Figure 10. Silver conducting paint is used to attach the base of the diode to the mounting and it also serves as one electrode. The other electrode is a .008 inch diameter stainless steel wire catwhisker.

Gold is generally evaporated onto the oxide surface to increase carrier collection efficiency. Dearnaley and Whitehead⁴ prefer to evaporate the gold onto the freshly etched surface and allow the oxidation to take place through the gold. They believe this procedure protects the silicon from contamination.

3. Diffused P-N Detectors

Diffused devices are made in an open tube electric furnace (Fig. 11). The silicon samples are placed on a quartz holder and inserted into a quartz tube which passes through the furnace. The diffusant is passed through the tube by means of a carrier gas and deposited on the surface of the silicon samples from whence diffusion takes place. The concentration of the diffusant is such that the amount deposited on the silicon provides a maximum surface concentration regardless of time. An alternate method is to paint the diffusant onto the surface of the silicon. In either case a shallow diffusion is desired in order to place the depletion region as close to the surface as possible. To do this a relatively low temperature (900°C) and a short diffusion time (10 minutes) is used. At the end of this time the furnace is turned off and allowed to cool slowly. Fast cooling or quenching sets up recombination centers within the silicon which shortens the minority carrier lifetime, and which in turn degrades the output pulse. The slow cooling, on the other hand, allows the diffusant atoms to properly substitute for the silicon atoms in the lattice and thus reform a perfect crystal.

After the silicon is removed from the furnace the reverse face and the four sides are hand lapped or etched to remove all traces of the diffusant. The samples are then mounted as before.

The diffusion of impurities into the silicon is governed by Fick's second law which states that the rate of accumulation of the impurity at any point is proportional to the divergence of the gradient of the impurity. The constant of proportionality is the diffusion constant (D). Mathematically stated it is:

$$\frac{dN}{dt} = D \nabla^2 N$$

Solution of this equation is simplified in that it need only be solved for the x direction. The equation then becomes:

$$\frac{dN}{dt} = D \frac{\partial^2 N}{\partial x^2}$$

Two boundary conditions are necessary to completely solve the equation. The laboratory set-up was designed to provide a constant surface source therefore $N(0,t) = N_s$, N_s is the surface concentration. The other boundary condition is a function of the distribution of the diffusant. In this case it is a step function.

$$\begin{aligned} N(x,0) = f(x) \qquad f(x) &= N_s \quad -\infty < x < 0 \\ &= 0 \quad 0 < x < \infty \end{aligned}$$

The solution of the equation is found in most texts on semiconductor technology.¹⁴ The solution is:

$$\begin{aligned} N(x) &= N_s \left[1 - \frac{2}{\sqrt{\pi}} \int_0^{\frac{x}{2\sqrt{Dt}}} e^{-\lambda^2} d\lambda \right] \\ &= N_s \left[1 - \operatorname{erf} \frac{x}{2\sqrt{Dt}} \right] \\ &= N_s \operatorname{erfc} \frac{x}{2\sqrt{Dt}} \end{aligned}$$

Group V elements are used as diffusants to form PN junctions in P type material. Specifically the phosphorus pentoxide compound (P_2O_5) was used. Its probable chemical reaction¹⁵ is $P_2O_5 + Si = P + \text{Phospho-silicate glass}$. The P_2O_5 is preheated to 225°C at which temperature it sublimes. The P_2O_5 vapor is carried to the silicon in the furnace with a carrier gas of nitrogen. This nitrogen is

... ..

$$\frac{1}{2} \left(\frac{1}{2} + \frac{1}{2} \right) = \frac{1}{2}$$

... ..

$$\frac{1}{2} \left(\frac{1}{2} + \frac{1}{2} \right) = \frac{1}{2}$$

... ..

$$\frac{1}{2} \left(\frac{1}{2} + \frac{1}{2} \right) = \frac{1}{2}$$

$$\frac{1}{2} \left(\frac{1}{2} + \frac{1}{2} \right) = \frac{1}{2}$$

... ..

obtained from the natural boil off from a dewar flask of liquid nitrogen.

Group III elements are used as diffusants to form PN junctions in N type silicon. Specifically two methods are used. First a suspension of Boron¹⁰ in mineral oil is painted on the surface of the silicon. It is then heated to a temperature of about 250°C in a vacuum chamber to drive off the mineral oil. The boron coated pieces of silicon are then placed in the diffusion oven for the 10 minute diffusion. The second method is to drift boron trichloride gas (BCl_3) over the silicon in the diffusion furnace. Its probable chemical reaction¹⁵ is $4\text{BCl}_3 + 3\text{Si} = 4\text{B} + 3\text{SiCl}_4$.

IV. EXPERIMENTAL UNITS AND RESULTS

1. Uranium Detectors.

a. Preparation of Experimental Units.

Eight experimental detectors were prepared from 100 ohm-cm N type silicon as described in section III. Two detectors were given initial shallow diffused p-n junctions (barrier depth .07 microns) using boron trichloride in the open tube electric furnace. Four units were given oxide coatings by exposure to a wet atmosphere overnight. Two of the oxide units were then coated with 5000 Å of gold. The final two units were freshly etched. All eight units were placed in the slotted holders (Fig. 5) and placed in the vacuum chamber (Fig. 7). Uranium-235 was evaporated from the spread tungsten filament (Fig. 6) in an initial vacuum of 5×10^{-7} mm of Hg. An area of .08 cm² was exposed on each unit. Upon completion of the uranium evaporation, the units were mounted (Fig. 10) and sprayed with an acrylic plastic.

Uranium is extremely difficult to evaporate. Preliminary investigations using tantalum, molybdenum and carbon vessels showed that uranium went into solution with these materials at elevated temperatures (about 1000° C). The only material that uranium would not go into solution with was tungsten. When the uranium melts it partially wets the tungsten forming a ball of molten uranium around the filament. An oxide crust forms on the surface of the ball which inhibits evaporation until temperatures of about 2200° C are reached. Unfortunately this ball generally migrates to one end of the filament thereby causing coatings of different thickness to be deposited on the silicon units. Since uranium is a metal,

THE HISTORY OF THE

1. THE HISTORY OF THE

2. THE HISTORY OF THE

3. THE HISTORY OF THE

4. THE HISTORY OF THE

5. THE HISTORY OF THE

6. THE HISTORY OF THE

7. THE HISTORY OF THE

8. THE HISTORY OF THE

9. THE HISTORY OF THE

10. THE HISTORY OF THE

11. THE HISTORY OF THE

12. THE HISTORY OF THE

13. THE HISTORY OF THE

14. THE HISTORY OF THE

15. THE HISTORY OF THE

16. THE HISTORY OF THE

17. THE HISTORY OF THE

18. THE HISTORY OF THE

19. THE HISTORY OF THE

20. THE HISTORY OF THE

21. THE HISTORY OF THE

22. THE HISTORY OF THE

23. THE HISTORY OF THE

24. THE HISTORY OF THE

25. THE HISTORY OF THE

26. THE HISTORY OF THE

27. THE HISTORY OF THE

28. THE HISTORY OF THE

29. THE HISTORY OF THE

30. THE HISTORY OF THE

31. THE HISTORY OF THE

32. THE HISTORY OF THE

33. THE HISTORY OF THE

34. THE HISTORY OF THE

35. THE HISTORY OF THE

36. THE HISTORY OF THE

37. THE HISTORY OF THE

38. THE HISTORY OF THE

39. THE HISTORY OF THE

40. THE HISTORY OF THE

41. THE HISTORY OF THE

42. THE HISTORY OF THE

43. THE HISTORY OF THE

44. THE HISTORY OF THE

45. THE HISTORY OF THE

46. THE HISTORY OF THE

47. THE HISTORY OF THE

48. THE HISTORY OF THE

49. THE HISTORY OF THE

50. THE HISTORY OF THE

51. THE HISTORY OF THE

52. THE HISTORY OF THE

53. THE HISTORY OF THE

54. THE HISTORY OF THE

55. THE HISTORY OF THE

56. THE HISTORY OF THE

57. THE HISTORY OF THE

58. THE HISTORY OF THE

59. THE HISTORY OF THE

60. THE HISTORY OF THE

61. THE HISTORY OF THE

62. THE HISTORY OF THE

63. THE HISTORY OF THE

64. THE HISTORY OF THE

65. THE HISTORY OF THE

66. THE HISTORY OF THE

67. THE HISTORY OF THE

68. THE HISTORY OF THE

69. THE HISTORY OF THE

70. THE HISTORY OF THE

71. THE HISTORY OF THE

72. THE HISTORY OF THE

73. THE HISTORY OF THE

74. THE HISTORY OF THE

75. THE HISTORY OF THE

76. THE HISTORY OF THE

77. THE HISTORY OF THE

78. THE HISTORY OF THE

79. THE HISTORY OF THE

80. THE HISTORY OF THE

81. THE HISTORY OF THE

82. THE HISTORY OF THE

83. THE HISTORY OF THE

84. THE HISTORY OF THE

85. THE HISTORY OF THE

86. THE HISTORY OF THE

87. THE HISTORY OF THE

88. THE HISTORY OF THE

89. THE HISTORY OF THE

90. THE HISTORY OF THE

91. THE HISTORY OF THE

92. THE HISTORY OF THE

93. THE HISTORY OF THE

94. THE HISTORY OF THE

95. THE HISTORY OF THE

96. THE HISTORY OF THE

97. THE HISTORY OF THE

98. THE HISTORY OF THE

99. THE HISTORY OF THE

100. THE HISTORY OF THE

the molten ball forms a conducting path with subsequent local cooling. The adjacent portions of the filament must then be excessively heated to provide sufficient heat for the evaporation. Another problem encountered was filament breakage before evaporation was complete. Initially .3 gram of uranium was placed on the filament. From past experience it was expected that about a 1 micron thick coating would be deposited on the silicon giving a thermal neutron efficiency of .3%.

The diode characteristics (Figures 14 to 17) were measured on a Tektronix 575 transistor curve tracer.

b. Results.

The uranium coated boron diffused units would detect neither the alpha decay of the U^{235} nor the fission fragments resulting from thermal neutron irradiation. It is believed this was caused by the poor diode characteristics of these units.

The uranium coated freshly etched units and surface oxide units would self count and also count fission fragments but their counting rate was extremely poor. Their counting efficiency for thermal neutrons was on the order of .0005%.

The uranium and gold coated surface oxide units were the best of the units tested. The efficiency of these units to thermal neutrons was on the order of .004%. Figure 12 shows the spectrum obtained from the alpha decay of the U^{235} . Figure 13 shows the spectrum of the energies of the fission fragments obtained as the result of thermal neutron irradiation. It is interesting to note that this offers a simple method of obtaining the mass distribution of the

THE UNIVERSITY OF CHICAGO

THE DIVISION OF THE PHYSICAL SCIENCES

THE DEPARTMENT OF CHEMISTRY

THE LABORATORY OF ORGANIC CHEMISTRY

THE LABORATORY OF PHYSICAL CHEMISTRY

THE LABORATORY OF ANALYTICAL CHEMISTRY

THE LABORATORY OF INORGANIC CHEMISTRY

THE LABORATORY OF BIOCHEMISTRY

THE LABORATORY OF MICROBIOLOGY

THE LABORATORY OF BOTANY

THE LABORATORY OF ZOOLOGY

THE LABORATORY OF AGRICULTURE

THE LABORATORY OF FORESTRY

THE LABORATORY OF MINING

THE LABORATORY OF METALLURGY

THE LABORATORY OF TEXTILES

THE LABORATORY OF LEATHERS

THE LABORATORY OF PAPER

THE LABORATORY OF GLASS

THE LABORATORY OF CERAMICS

THE LABORATORY OF RUBBER

THE LABORATORY OF PLASTICS

THE LABORATORY OF COLORED GLASS

THE LABORATORY OF OPTICS

THE LABORATORY OF ELECTRICITY

THE LABORATORY OF MAGNETISM

THE LABORATORY OF THERMODYNAMICS

THE LABORATORY OF STATISTICS

fission fragments. The energies shown are only approximate and were obtained by scaling from the 4.58 Mev self count peak. The energies of the two peaks are approximately 40 Mev lower than was expected (Section II-7). This discrepancy can partially be explained by the fact that fission fragments are highly ionized and lose most of their energy in the initial part of their path, part of which is beyond a diffusion length from the depletion region. The alpha particles, however, lose most of their energy toward the end of their path thus they lose very little energy prior to entering the depletion region.

2. B¹⁰ Detectors

a. Preparation of Experimental Units.

Four experimental B¹⁰ detectors were prepared, using 2000 ohm-cm N type silicon. Two units received an initial boron diffused p-n junction (.08 microns), using boron trichloride in the open tube electric furnace. They were subsequently painted with B¹⁰ enriched 90-92% (amorphous in oil). The oil was driven off in a vacuum chamber by heating to 250° C for 10 minutes. The other two units were painted with the enriched B¹⁰ directly on the freshly etched surface. The oil was removed in the same manner. All four units were then placed in the furnace at 900°C for 10 minutes. The four units were then mounted the same as the uranium detectors and sprayed with plastic. The diode characteristics are as shown in Figures 18 and 19.

b. Results

The two units having the preformed p-n junctions did not operate as well as those that were given only the B¹⁰. Figures 20, 21 and 22 show the reaction particle energy spectra, to a 10⁶ neutrons/cm² sec thermal neutron beam, for 0,5 and 10 volts reverse bias. The efficiency to thermal neutrons of the best of the four units was about 1.3%.

REIGN OF KING CHARLES THE FIRST

THE first year of his Majesty's reign was spent in settling the government, and in settling the peace of the kingdom. The king was very diligent in his duties, and was very popular among his subjects. He was very generous to his subjects, and was very merciful to his enemies. He was very brave in his wars, and was very successful in his battles. He was very wise in his councils, and was very prudent in his actions. He was very kind to his subjects, and was very generous to his enemies. He was very brave in his wars, and was very successful in his battles. He was very wise in his councils, and was very prudent in his actions. He was very kind to his subjects, and was very generous to his enemies.

THE SECOND YEAR

THE second year of his Majesty's reign was spent in settling the government, and in settling the peace of the kingdom. The king was very diligent in his duties, and was very popular among his subjects. He was very generous to his subjects, and was very merciful to his enemies. He was very brave in his wars, and was very successful in his battles. He was very wise in his councils, and was very prudent in his actions. He was very kind to his subjects, and was very generous to his enemies.

3. Li⁶ Detectors

a. Preparation of Experimental Units.

Two experimental Li⁶ detectors were prepared from 1000 ohm-cm P type silicon. Li⁶ (amorphous in oil) was painted on the freshly etched silicon surface. These units were then placed in a vacuum chamber and heated at 250° C for 10 minutes to drive off the oil. The temperature was then raised to 450° C for 90 seconds to diffuse the lithium into the silicon producing a barrier depth of 154 microns. The units were then mounted.

b. Results

Figure 23 shows the reaction particle energy spectrum to a 10⁶ neutrons/cm² sec thermal neutron beam. The maximum energy of the triton (2.73 Mev) is shown on Figure 23. By scaling this energy to the small peak, the large peak indicates an energy of 2.05 Mev, which is the energy expected of the alpha particle. The efficiency of these detectors to thermal neutrons is about .4%. The ratio of the efficiencies of the Li⁶ and B¹⁰ approximately reflects the ratio of their cross sections.

$$B^{10} \sigma_{n\alpha} - 4020 \text{ barns}$$

$$Li^6 \sigma_{n\alpha} - 950 \text{ barns}$$

THE UNIVERSITY OF CHICAGO

The University of Chicago is a private research university located in Chicago, Illinois. It was founded in 1837 and is one of the oldest and most prestigious universities in the United States. The university is known for its commitment to academic excellence and its diverse student body. It has a long history of producing world-class scholars and leaders in various fields of study. The university's research output is highly influential, and it has a strong reputation for its contributions to knowledge and society.

CHICAGO

Chicago is a major city in the United States, known for its vibrant culture, diverse population, and significant contributions to various fields of study. The city is home to several world-class universities, including the University of Chicago, which is a leading institution for research and education. Chicago's location on the shores of Lake Michigan provides a unique setting for its academic and cultural activities. The city is also known for its architectural landmarks, including the Willis Tower, and its rich history of innovation and progress.

$$\frac{1}{2} \log \frac{1}{2} = -\frac{1}{2} \log 2$$

V. ELECTRONICS

Figure 24 is a block diagram of the electronics test equipment. The heart of the system is a low noise pre-amplifier, designed by F. S. Goulding. A schematic diagram of an improved version of this pre-amplifier may be found in Reference 5, Figure 9. The 256 channel analyzer (Radiation Counting Laboratory) requires input pulses between 0 and 100 volts with .5 microsecond rise times. The linear amplifier (UCRL Kaifer) compliments the analyzer.

The detector pulse has a rise time on the order of nanoseconds. The pulse is then integrated in both the pre-amplifier (rise time .4 microseconds) and the linear amplifier (rise time .5 microseconds) before going to the analyzer. A .55 microsecond clipping line was installed between the pre-amplifier and the linear amplifier to eliminate the low frequency noise. It was noted that the reverse current characteristics of the detectors was a direct indication of the noise to be expected.

It is a very common mistake to suppose that the
only way to get the best results is to use the
best materials. It is true that the best materials
will give the best results, but it is equally true
that the best results can be obtained by using
the best methods. The best methods are those
which are based on a thorough knowledge of the
subject, and which are applied with skill and
care. The best results are those which are
obtained by the use of the best materials and
the best methods. It is a very common mistake
to suppose that the only way to get the best
results is to use the best materials. It is true
that the best materials will give the best
results, but it is equally true that the best
results can be obtained by using the best
methods. The best methods are those which
are based on a thorough knowledge of the
subject, and which are applied with skill and
care. The best results are those which are
obtained by the use of the best materials and
the best methods.

VI. CONCLUSIONS

Additional research is necessary to improve the efficiency of these detectors. The B^{10} detectors appear to hold the most promise for the detection of slow neutrons owing to their large cross section and ease of fabrication. The use of a guard ring⁵ on these detectors would greatly improve their diode characteristics thus enabling the use of larger reverse bias voltages.

Possible uses of these devices include: Space probe detection units; Reactor core flux mapping; Neutron beam collimation and exploration; Medical research; and Neutron spectroscopy.

ACKNOWLEDGEMENTS

I wish to thank Dr. Joseph E. Schwager, CDR, USN for his guidance during the course of this work. Conversations with Dr. Donald White on the interpretation of data were both opportune and enlightening. The assistance of the entire staff of the Livermore Pool Type Reactor Facility is profoundly appreciated. I am deeply indebted to Dr. Albert Kirschbaum for encouraging and supporting this experimental program and to Professors A. Sheingold and E. C. Crittenden who have motivated my interest in this field.

BIBLIOGRAPHY

1. S. S. Friedland, J. W. Mayer and J. S. Wiggins, *Nucleonics* 2, 54 (1960).
2. G. L. Miller, W. L. Brown, P. F. Donovan and I. M. Mackintosh, "Silicon p-n Junction Radiation Detectors", *Proceedings of the Seventh Scintillation Counter Symposium, IRE Transactions on Nuclear Science NS-7*, 185 (1960).
3. J. W. Mayer, *J. Appl. Phys.*, 12, 1937 (1959).
4. G. Dearnaley and A. B. Whitehead, *Nucleonics*, 1, 72 (1961).
5. F. S. Goulding and W. L. Hanson, UCRL 9436.
6. J. H. Elliott, UCRL 9538.
7. A. R. Jones, *Nucleonics*, 10, 86 (1960).
8. R. Steinberg, *Nucleonics*, 2, 85 (1960).
9. R. V. Babcock, R. E. Davis, S. L. Ruby, K. H. Sun and E. D. Wolley, *Nucleonics*, 4, 116 (1959).
10. C. Kittel, Introduction to Solid State Physics (Wiley, New York, 1956).
11. J. N. Shive, The Properties, Physics, and Design of Semiconductor Devices (Van Nostrand, Princeton, 1959).
12. W. Shockley, Electrons and Holes in Semiconductors (Van Nostrand, Princeton, 1950).
13. K. G. McKay and K. B. McAfee, *Phys. Rev.* 91, 1079 (1953).
14. A. K. Jonscher, Principles of Semiconductor Device Operation (Wiley, New York, 1960).
15. F. J. Biondi, Editor, Transistor Technology, Vol III, (Van Nostrand, Princeton, 1958).
16. W. E. Shoupp, Westinghouse Electric Corp. Periodic Chart with Nuclear Data (1960).
17. D. J. Hughes and J. A. Harvey, Neutron Cross Sections (BNL 325, Brookhaven National Laboratory, Upton, New York, 1953).
18. E. Segre, Experimental Nuclear Physics (Wiley, New York, 1953).
19. D. Baker, *J. Scien. Insts.*, 36, 145, (1959).

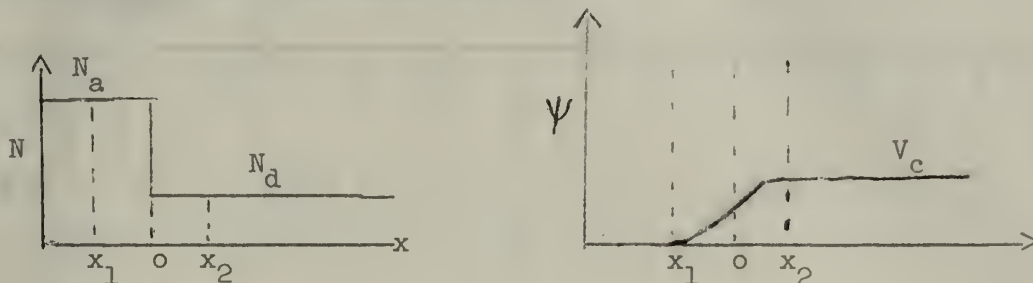
INDEX

1. General Introduction 1
2. Physical Properties of Matter 2
3. Chemical Properties of Matter 3
4. Atomic Structure 4
5. Molecular Structure 5
6. Crystal Structure 6
7. Thermal Properties 7
8. Electrical Properties 8
9. Magnetic Properties 9
10. Optical Properties 10
11. Acoustic Properties 11
12. Radioactive Properties 12
13. Biological Properties 13
14. Environmental Properties 14
15. Industrial Properties 15
16. Medical Properties 16
17. Agricultural Properties 17
18. Marine Properties 18
19. Atmospheric Properties 19
20. Geological Properties 20
21. Historical Properties 21
22. Future Properties 22
23. Conclusion 23

Appendix A

Solution of Poisson's Equation for a Surface Barrier Junction..

An abrupt junction or shottky type barrier occurs when the semiconductor dopant changes abruptly from N to P type or vice versa in the relatively short distance of 1 to 2 atomic distances. This solution is applicable to surface barrier, alloyed and shallow diffused diodes.



The above two figures illustrate the dopant concentration (N) and potential distribution in initially N type silicon with a P type surface concentration. For convenience the origin is considered at the point where the concentration changes.

N_a = Acceptor surface concentration

N_d = Donor concentration

$o-x_1$ = Width of the depletion region in the P type material

x_2-o = Width of the depletion region in the N type material

V_c = Voltage across the equivalent capacitor

$$V_c = V_B + \phi_a - \phi_d$$

V_B = Reverse bias

ϕ_a = Fermi potential of the acceptor material

ϕ_d = Fermi potential of the donor material

1. Introduction

The purpose of this paper is to study the properties of the function $f(x)$ defined by the equation $f(x) = \int_0^x f(t) dt$. It is well known that the only function satisfying this equation is the zero function. However, we will show that there are non-zero functions satisfying this equation if we allow $f(x)$ to be a distribution. In the first section, we will define distributions and show that the equation $f(x) = \int_0^x f(t) dt$ has non-zero solutions in the space of distributions. In the second section, we will study the properties of these solutions and show that they are all multiples of the Dirac delta function $\delta(x)$.



In the first section, we will define distributions and show that the equation $f(x) = \int_0^x f(t) dt$ has non-zero solutions in the space of distributions. In the second section, we will study the properties of these solutions and show that they are all multiples of the Dirac delta function $\delta(x)$.

Let $f(x)$ be a function defined on the real line. We say that $f(x)$ is a distribution if it satisfies the equation $f(x) = \int_0^x f(t) dt$. It is well known that the only function satisfying this equation is the zero function. However, we will show that there are non-zero functions satisfying this equation if we allow $f(x)$ to be a distribution. In the first section, we will define distributions and show that the equation $f(x) = \int_0^x f(t) dt$ has non-zero solutions in the space of distributions. In the second section, we will study the properties of these solutions and show that they are all multiples of the Dirac delta function $\delta(x)$.

Let $f(x)$ be a function defined on the real line. We say that $f(x)$ is a distribution if it satisfies the equation $f(x) = \int_0^x f(t) dt$. It is well known that the only function satisfying this equation is the zero function. However, we will show that there are non-zero functions satisfying this equation if we allow $f(x)$ to be a distribution. In the first section, we will define distributions and show that the equation $f(x) = \int_0^x f(t) dt$ has non-zero solutions in the space of distributions. In the second section, we will study the properties of these solutions and show that they are all multiples of the Dirac delta function $\delta(x)$.

The boundary conditions taken from the figures are:

$$\begin{array}{ll} \left. \frac{d\psi_a}{dx} \right|_{x=x_1} = 0 & \left. \frac{d\psi_d}{dx} \right|_{x=x_2} = 0 \\ \left. \psi_a \right|_{x=x_1} = 0 & \left. \psi_d \right|_{x=x_2} = V_c \end{array}$$

$$\psi \text{ and } \frac{d\psi}{dx} \text{ are continuous at } x = 0$$

$$\nabla \cdot D = \rho$$

$$D = \epsilon E$$

$$E = -\nabla \psi$$

$$\therefore \nabla^2 \psi = -\frac{\rho}{\epsilon}$$

$$\rho_a = -q(N_a + n - p)$$

n = electron concentration

p = hole concentration

$$\text{Assume } N_a \gg (n - p)$$

$$\therefore \rho_a = -q N_a$$

q = electronic charge

$$\text{also } \rho_d = +q N_d$$

$$\nabla^2 \psi_a = \frac{q N_a}{\epsilon}$$

All the y and z donations drop out since the junction is in the $y z$ plane.

$$\text{then } \frac{d^2 \psi_a}{dx^2} = \frac{q N_a}{\epsilon}$$

$$\left. \frac{d\psi_a}{dx} \right|_{x_1}^x = \frac{q N_a}{\epsilon} x \Big|_{x_1}^x$$

$$\frac{d\psi_a}{dx} = \frac{q N_a}{\epsilon} (x - x_1) \quad (A-1)$$

Let $f(x) = \frac{1}{x^2}$ and $g(x) = \frac{1}{x^3}$

$$f(x) = \frac{1}{x^2}$$

$$g(x) = \frac{1}{x^3}$$

$$f'(x) = -\frac{2}{x^3}$$

$$g'(x) = -\frac{3}{x^4}$$

$$f(x)g'(x) - f'(x)g(x) = \frac{1}{x^2} \cdot -\frac{3}{x^4} - \left(-\frac{2}{x^3}\right) \cdot \frac{1}{x^3}$$

$$= -\frac{3}{x^6} + \frac{2}{x^6}$$

$$= -\frac{1}{x^6}$$

$$= -x^{-6}$$

$$= -\frac{1}{x^6} \therefore$$

$$(f \cdot g)' = -\frac{1}{x^6}$$

$$\frac{d}{dx} \left(\frac{1}{x^2} \cdot \frac{1}{x^3} \right) = -\frac{1}{x^6}$$

$$\frac{d}{dx} \left(\frac{1}{x^5} \right) = -\frac{1}{x^6}$$

$$\frac{d}{dx} x^{-5} = -x^{-6}$$

$$(f \cdot g)' = -\frac{1}{x^6}$$

$$f'g + fg' = -\frac{1}{x^6} \therefore$$

$$\frac{d}{dx} \left(\frac{1}{x^2} \cdot \frac{1}{x^3} \right) = -\frac{1}{x^6}$$

$$\frac{d}{dx} x^{-5} = -x^{-6}$$

$$\frac{d}{dx} x^{-5} = -\frac{d}{dx} x^{-5}$$

$$\int \frac{d}{dx} x^{-5} = \int -\frac{d}{dx} x^{-5}$$

$$(f \cdot g)'$$

$$(f \cdot g)' = \frac{f'g}{x} + \frac{fg'}{x}$$

$$\psi_a \Big|_{x_1}^x = \frac{q N_a}{\epsilon} \left(\frac{x^2}{2} - x_1 x \right) \Big|_{x_1}^x$$

$$\psi_a = \frac{q N_a}{2 \epsilon} (x^2 - 2 x_1 x + x_1^2)$$

$$\psi_a = \frac{q N_a}{2 \epsilon} (x - x_1)^2 \quad (A-2)$$

The solution for the acceptor region follows the same method.

$$\frac{d\psi_a}{dx} = - \frac{q N_d}{\epsilon} (x - x_2) \quad (A-3)$$

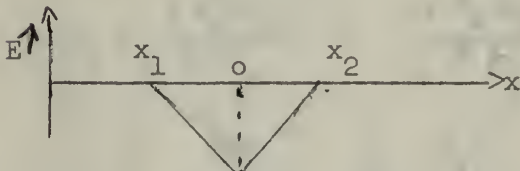
$$\psi_d \Big|_{x_2}^x = - \frac{q N_d}{2 \epsilon} (x^2 - 2 x_2 x) \Big|_{x_2}^x$$

$$\psi_d = v_c - \frac{q N_d}{2 \epsilon} (x - x_2)^2 \quad (A-4)$$

From equations A-1 and A-3 the electric field is :

$$E_a = - \frac{q N_a}{\epsilon} (x - x_1) \quad (A-5)$$

$$E_d = + \frac{q N_d}{\epsilon} (x - x_2) \quad (A-6)$$



at $x = 0$ $\frac{d\psi_a}{dx} = \frac{d\psi_d}{dx}$

$$\begin{aligned} \frac{q}{\epsilon} N_a (0 - x_1) &= - \frac{q}{\epsilon} N_d (0 - x_2) \\ &= \frac{q}{\epsilon} N_d (x_2 - 0) \end{aligned}$$

$(0 - x_1) = d_a$ = depletion region in the P material

$(x_2 - 0) = d_d$ = depletion region in the N material

$$d_a = \frac{N_d}{N_a} d_d \quad (A-7)$$

$$\int (x^2 + 3x + \frac{4}{x}) dx$$

$$\int (x^2 + 3x + \frac{4}{x}) dx = \frac{x^3}{3} + \frac{3x^2}{2} + 4 \ln|x| + C$$

(1-2) $\int (x^2 - 5) dx = \frac{x^3}{3} - 5x + C$

Exercise 1: Find the integral of the following functions.

(1-3) $\int (x^3 - 2x + \frac{1}{x}) dx = \frac{x^4}{4} - x^2 + \ln|x| + C$

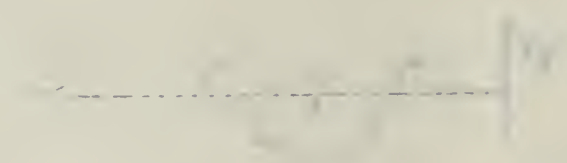
(1-4) $\int (x^2 + 4x - \frac{3}{x}) dx = \frac{x^3}{3} + 2x^2 - 3 \ln|x| + C$

(1-5) $\int (x^2 + 1) dx = \frac{x^3}{3} + x + C$

Exercise 2: Find the area under the curve y = x^2 from x = 0 to x = 2.

(2-1) $\int_0^2 x^2 dx = \frac{x^3}{3} \Big|_0^2 = \frac{8}{3}$

(2-2) $\int_1^4 (x + \frac{1}{x}) dx = \frac{x^2}{2} + \ln|x| \Big|_1^4 = \frac{15}{2}$



$$\frac{d}{dx} \left(\frac{x^3}{3} \right) = x^2$$

(2-3) $\int_0^1 (x^2 + x) dx = \frac{x^3}{3} + \frac{x^2}{2} \Big|_0^1 = \frac{5}{6}$

(2-4) $\int_1^2 \frac{1}{x} dx = \ln|x| \Big|_1^2 = \ln 2$

Exercise 3: Find the volume of the solid generated by revolving the region bounded by y = x^2 and y = 4 about the y-axis.

Exercise 4: Find the volume of the solid generated by revolving the region bounded by y = x^2 and y = 4 about the x-axis.

(3-1)

Equation (A-7) shows that for equal concentrations the depletion region on each side of the barrier is equal. Realistically this does not occur. For high resistivity material ($N_d \ll N_a$) the depletion region approaches zero on the acceptor side hence the entire electric field is located on the donor side.

The total depletion region (d) is

$$\begin{aligned} d &= d_a + d_d \\ &= \frac{N_d}{N_a} d_d + d_d \\ d &= \left(1 + \frac{N_d}{N_a} \right) d_d \end{aligned} \quad (A-8)$$

at $x = 0 \quad \psi_a = \psi_d$

$$\frac{q N_a}{2 \epsilon} (d_a)^2 = V_c - \frac{q N_d}{2 \epsilon} (-d_d)^2$$

$$\frac{q N_a}{2 \epsilon} \left(\frac{N_d}{N_a} d_d \right)^2 = V_c - \frac{q N_d}{2 \epsilon} d_d^2$$

$$V_c = \frac{q N_d^2 d_d^2}{2 \epsilon N_a} + \frac{q N_d d_d^2}{2 \epsilon}$$

$$= d_d^2 \frac{q N_d}{2 \epsilon} \left[1 + \frac{N_d}{N_a} \right]$$

$$d_d = \left[\frac{2 \epsilon V_c}{q N_d \left(1 + \frac{N_d}{N_a} \right)} \right]^{\frac{1}{2}} \quad (A-9)$$

Combining (A-8) and (A-9)

$$d = \left[\frac{2 \epsilon V_c \left(1 + \frac{N_d}{N_a} \right)}{q N_d} \right]^{\frac{1}{2}} \quad (A-10)$$

(1) $f(x)$ is a function of x and y is a function of x .
 (2) $f(x)$ is a function of x and y is a function of x .
 (3) $f(x)$ is a function of x and y is a function of x .
 (4) $f(x)$ is a function of x and y is a function of x .

$$f(x) = \frac{1}{x^2} + \frac{1}{x^3}$$

$$f(x) = \frac{1}{x^2} + \frac{1}{x^3}$$

(1)

$$f(x) = \frac{1}{x^2} + \frac{1}{x^3}$$

$$f(x) = \frac{1}{x^2} + \frac{1}{x^3}$$

$$f(x) = \frac{1}{x^2} + \frac{1}{x^3}$$

$$f(x) = \frac{1}{x^2} + \frac{1}{x^3}$$

$$f(x) = \frac{1}{x^2} + \frac{1}{x^3}$$

$$f(x) = \frac{1}{x^2} + \frac{1}{x^3}$$

(2)

$$f(x) = \frac{1}{x^2} + \frac{1}{x^3}$$

$$f(x) = \frac{1}{x^2} + \frac{1}{x^3}$$

(3)

$$f(x) = \frac{1}{x^2} + \frac{1}{x^3}$$

Since ($N_a \gg N_d$), the term $\frac{N_d}{N_a}$ approaches zero. The depletion region becomes wider as N_d becomes smaller. Thus by using higher resistivity material the depletion region can be extended. Another means of extending the depletion region is by use of higher reverse bias voltages ($V_c = V_B + \phi_a - \phi_d$).

Since charge must be conserved

$$Q_a = Q_d$$

$$Q_d = q N_d d_d$$

$$= \left[\frac{2 \epsilon q N_d V_c}{\left(1 + \frac{N_d}{N_a}\right)} \right]^{\frac{1}{2}} \quad (A-11)$$

$$C = \frac{dQ}{dV} = \frac{1}{2} \left[\frac{2 \epsilon q N_d V_c}{1 + \frac{N_d}{N_a}} \right]^{-\frac{1}{2}} \frac{2 \epsilon q N_d}{1 + \frac{N_d}{N_a}}$$

$$= \frac{\epsilon q N_d}{1 + \frac{N_d}{N_a}} \left[\frac{1 + \frac{N_d}{N_a}}{2 \epsilon q N_d V_c} \right]^{\frac{1}{2}}$$

$$C = \left[\frac{\epsilon q N_d}{2 V_c \left(1 + \frac{N_d}{N_a}\right)} \right]^{\frac{1}{2}} = \frac{\epsilon}{d} \quad (A-12)$$

The expression for capacitance is recognizable as the same as for a parallel plate capacitor and varies directly as the square root of the donor concentration and inversely with the square root of the reverse bias.

Let $f(x) = \frac{1}{x^2}$ and $g(x) = \frac{1}{x^3}$. Then $f(x)g(x) = \frac{1}{x^5}$.
 We want to find $\frac{d}{dx} \left(\frac{1}{x^5} \right)$.
 Using the power rule, $\frac{d}{dx} x^{-5} = -5x^{-6} = -\frac{5}{x^6}$.

$$\frac{d}{dx} \left(\frac{1}{x^5} \right) = -\frac{5}{x^6}$$

$$f(x) = \frac{1}{x^2}$$

$$g(x) = \frac{1}{x^3}$$

$$\frac{f(x)g(x)}{f(x)^2 + g(x)^2} = \frac{\frac{1}{x^5}}{\frac{1}{x^4} + \frac{1}{x^6}} = \frac{\frac{1}{x^5}}{\frac{x^2 + 1}{x^6}} = \frac{x}{x^2 + 1}$$

$$(1)$$

$$\frac{d}{dx} \left(\frac{x^2 + 1}{x^2 + 1} \right) = \frac{d}{dx} (1) = 0$$

$$\frac{d}{dx} \left(\frac{x^2 + 1}{x^2 + 1} \right) = \frac{d}{dx} (1) = 0$$

$$(2)$$

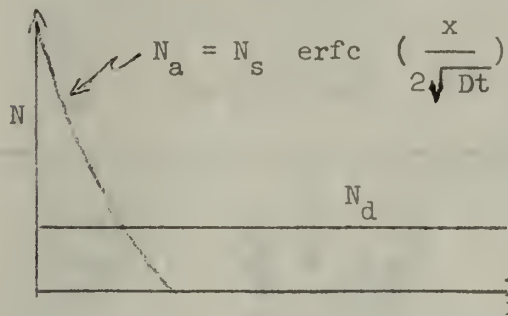
$$\frac{d}{dx} \left(\frac{x^2 + 1}{x^2 + 1} \right) = \frac{d}{dx} (1) = 0$$

Let $f(x) = \frac{1}{x^2}$ and $g(x) = \frac{1}{x^3}$. Then $f(x)g(x) = \frac{1}{x^5}$.
 We want to find $\frac{d}{dx} \left(\frac{1}{x^5} \right)$.
 Using the power rule, $\frac{d}{dx} x^{-5} = -5x^{-6} = -\frac{5}{x^6}$.

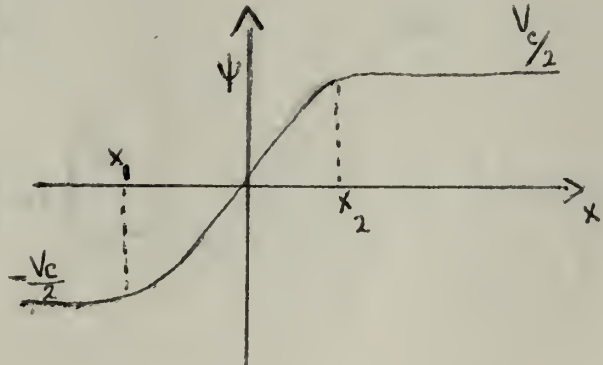
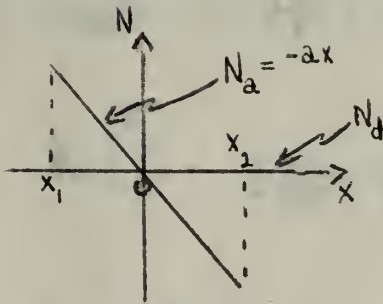
Appendix B

Solution of Poisson's Equation for a Graded Junction.

The graded junction solution is applicable to the case of a grown p-n junction or a diffused p-n junction when the diffusion is carried out over a relatively long period of time.



The equation for N_a is the solution of the diffusion equation for a constant surface source. As a first approximation it can be assumed that N_a is a straight line in the vicinity where it crosses N_d



Boundary Conditions

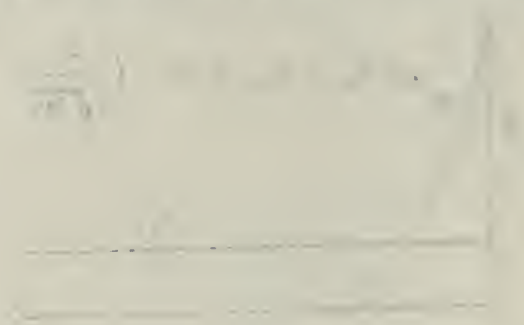
$$\left. \frac{d\psi_a}{dx} \right|_{x=x_1} = 0$$

$$\left. \frac{d\psi_d}{dx} \right|_{x=x_2} = 0$$

PROBLEM 1

Consider the function $f(x) = \sin(x)$ defined on the interval $[0, 2\pi]$.

(a) Find the maximum and minimum values of $f(x)$ on the interval $[0, 2\pi]$.
 (b) Find the points on the graph of $f(x)$ where the tangent line is horizontal.



(c) Find the area under the curve $y = \sin(x)$ from $x = 0$ to $x = \pi$.
 (d) Find the volume of the solid generated by revolving the curve $y = \sin(x)$ around the y-axis for x from 0 to π .



$$f(x) = \sin(x)$$

$$f'(x) = \cos(x)$$

$$\psi_a \Big|_{x=x_1} = -\frac{V_c}{2}$$

$$\psi_d \Big|_{x=x_2} = \frac{V_c}{2}$$

$$\psi_1 = \psi_2 \text{ at } x = 0$$

$$x_1 = -x_2$$

$$N_a = -ax$$

$$\rho_a = -q N_a = q ax$$

$$\frac{d^2 \psi_a}{dx^2} = -\frac{\rho_a}{\epsilon} = -\frac{q ax}{\epsilon}$$

$$\frac{d \psi_a}{dx} \Big|_{x_1}^x = -\frac{q a}{\epsilon} \frac{x^2}{2} \Big|_{x_1}^x$$

$$\frac{d \psi_a}{dx} = -\frac{q a}{2 \epsilon} (x^2 - x_1^2) \quad (B-1)$$

$$\psi_a \Big|_{x_1}^{x_2} = -\frac{q a}{2 \epsilon} \left(\frac{x^3}{3} - x_1^2 x \right) \Big|_{x_1}^{x_2} = -x_2$$

$$V_c = \frac{q a}{2 \epsilon} \frac{4}{3} x_2^3$$

$$x_2 = \left[\frac{3 \epsilon V_c}{2 q a} \right]^{1/3}$$

$$d = 2 x_2 = \left[\frac{12 \epsilon V_c}{q a} \right]^{1/3} \quad (B-2)$$

$$4 - 2 \frac{1}{2} \frac{1}{2} \frac{1}{2}$$

$$\frac{1}{2} = \frac{1}{2} \frac{1}{2} \frac{1}{2}$$

$$1 - \frac{1}{2} \frac{1}{2} \frac{1}{2}$$

$$\frac{1}{2} = \frac{1}{2} \frac{1}{2} \frac{1}{2}$$

$$\frac{1}{2} = \frac{1}{2} \frac{1}{2} \frac{1}{2}$$

$$\frac{1}{2} = \frac{1}{2} \frac{1}{2} \frac{1}{2}$$

$$\frac{1}{2} = \frac{1}{2} \frac{1}{2} \frac{1}{2}$$

$$\frac{1}{2} = \frac{1}{2} \frac{1}{2} \frac{1}{2}$$

$$(2-1)$$

$$\left(\frac{1}{2} - \frac{1}{2} \right) \frac{1}{2} = \frac{1}{2} \frac{1}{2}$$

$$\left(\frac{1}{2} - \frac{1}{2} \right) \frac{1}{2} = \frac{1}{2} \frac{1}{2}$$

$$\frac{1}{2} = \frac{1}{2} \frac{1}{2} \frac{1}{2}$$

$$\frac{1}{2} = \frac{1}{2} \frac{1}{2} \frac{1}{2}$$

$$\frac{1}{2} = \frac{1}{2} \frac{1}{2} \frac{1}{2}$$

$$(2-2)$$

Equation (B-2) shows that the depletion region varies directly with the cube root of the applied reverse bias.

$$C = \frac{dQ}{dV}$$

$$dQ_a = -q N_a dx = q a x dx$$

$$Q_a \Big|_0^{x=x_2} = \frac{q a x^2}{2} \Big|_0^{x=x_2}$$

$$Q_a = \frac{q a x_2^2}{2} = \frac{q a}{2} \left[\frac{3 \epsilon V_c}{2 q a} \right]^{2/3}$$

$$\frac{dQ_a}{dV} = C = \frac{\epsilon}{2 \left[\frac{3 \epsilon V_c}{2 q a} \right]^{1/3}} = \frac{\epsilon}{d} \quad (B-3)$$

Equation (B-3) is the equation of a parallel plate capacitor and it shows that the capacitance varies inversely with the cube root of the applied reverse bias.

Let $f(x)$ be a function defined on the interval $[a, b]$. Then the definite integral of $f(x)$ from a to b is denoted by

$$\int_a^b f(x) dx$$

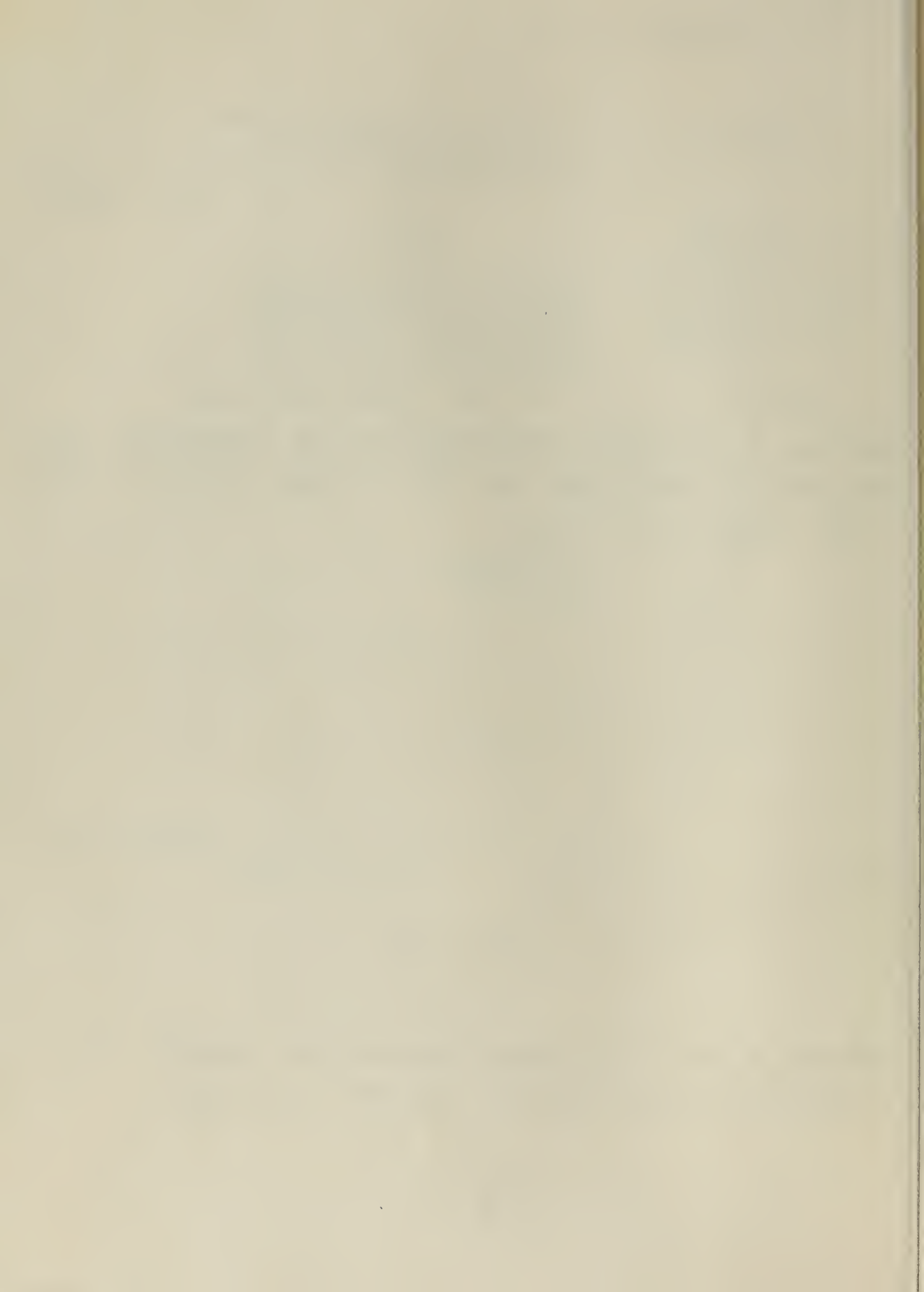
$$= \lim_{n \rightarrow \infty} \sum_{k=1}^n f(x_k^*) \Delta x_k$$

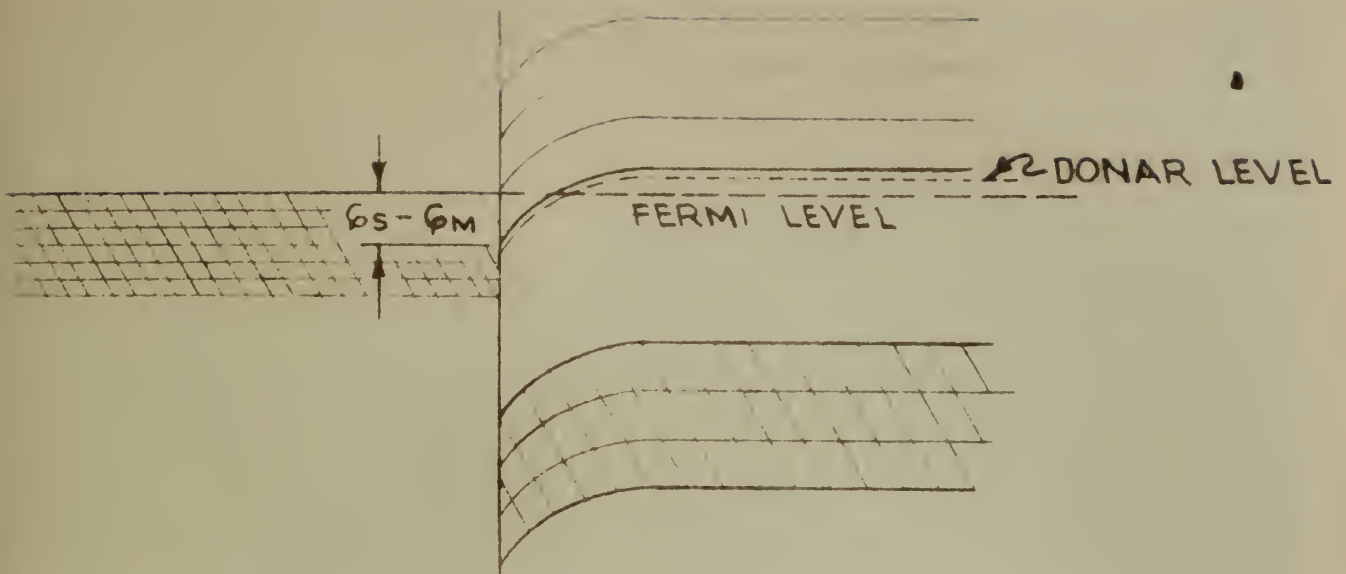
$$= \lim_{n \rightarrow \infty} \left(\sum_{k=1}^n f(x_k^*) \right) \Delta x_k$$

$$= \lim_{n \rightarrow \infty} \left(\frac{f(a) + f(b)}{2} \right) \Delta x_k$$

$$(4-5) \quad \frac{1}{x} = \frac{1}{x} \cdot \frac{x}{x} = \frac{x}{x^2} = \frac{1}{x^2}$$

Let $f(x)$ be a function defined on the interval $[a, b]$. Then the definite integral of $f(x)$ from a to b is denoted by





METAL TO N TYPE SEMICONDUCTOR OHMIC CONTACT.

Fig. 3

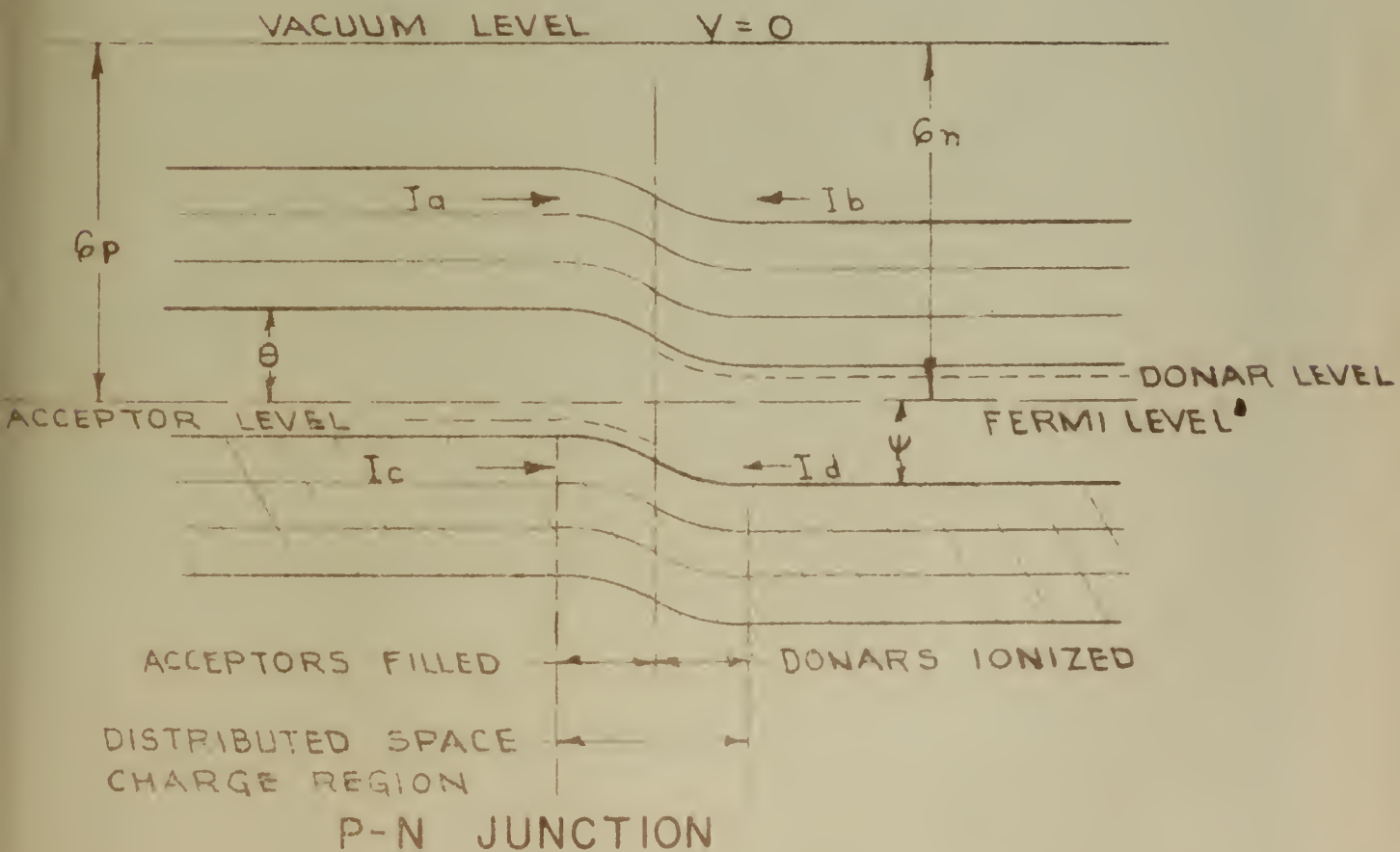
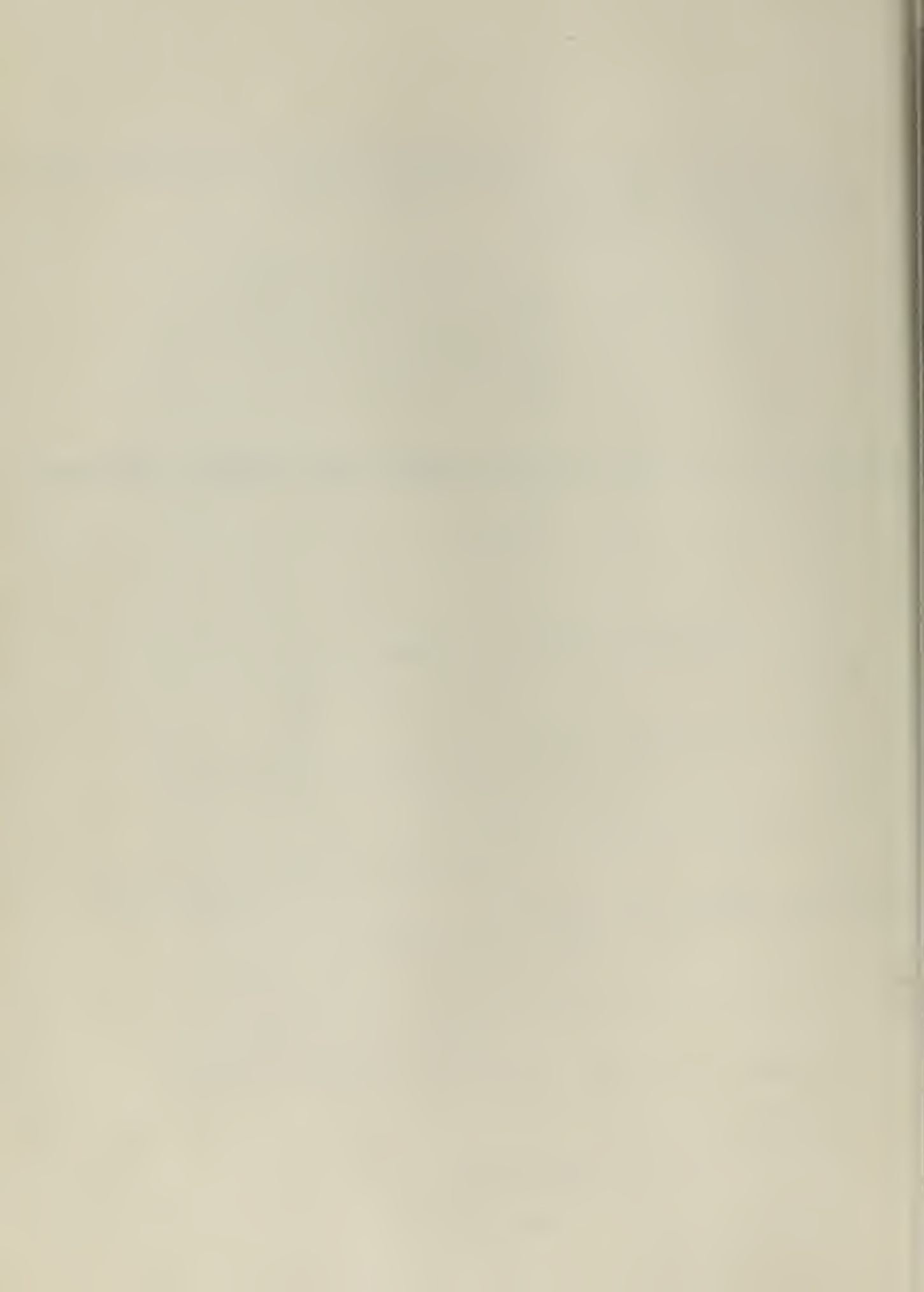


Fig. 4



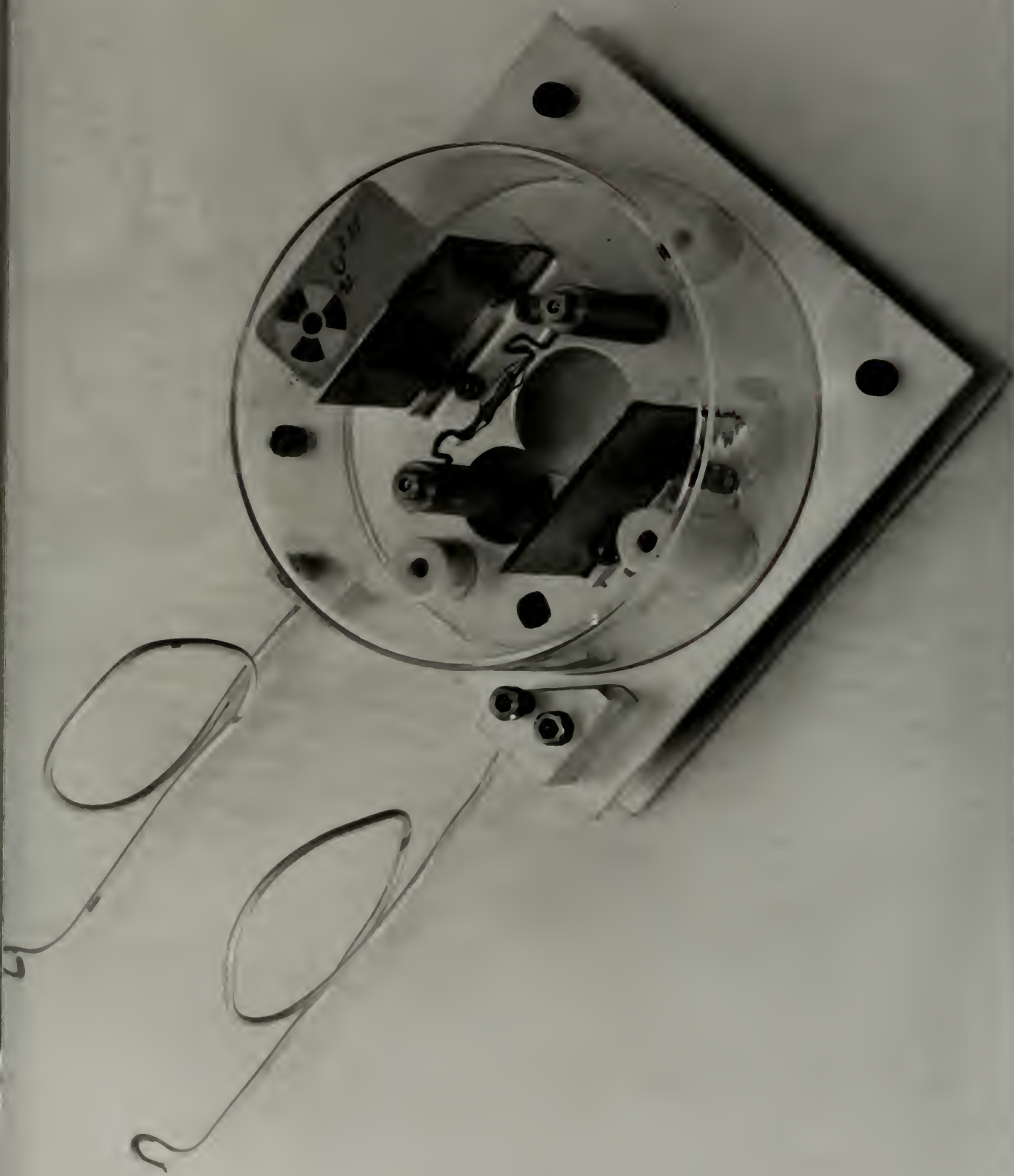


Figure 5 - Uranium evaporation jig

LRL Livermore

Graphic Arts Dept.

Neg. No. 24111

UNCLASSIFIED

WITHOUT CAPTION

NOT FOR PUBLICATION

WITHOUT PERMISSION



Figure 6 - Filament detail

LRI Livermore
Graphic Arts Dept.
Neg. No. 24110
UNCLASSIFIED
WITHOUT CAPTION
NO. FOR PUBLICATION
WITHOUT PERMISSION

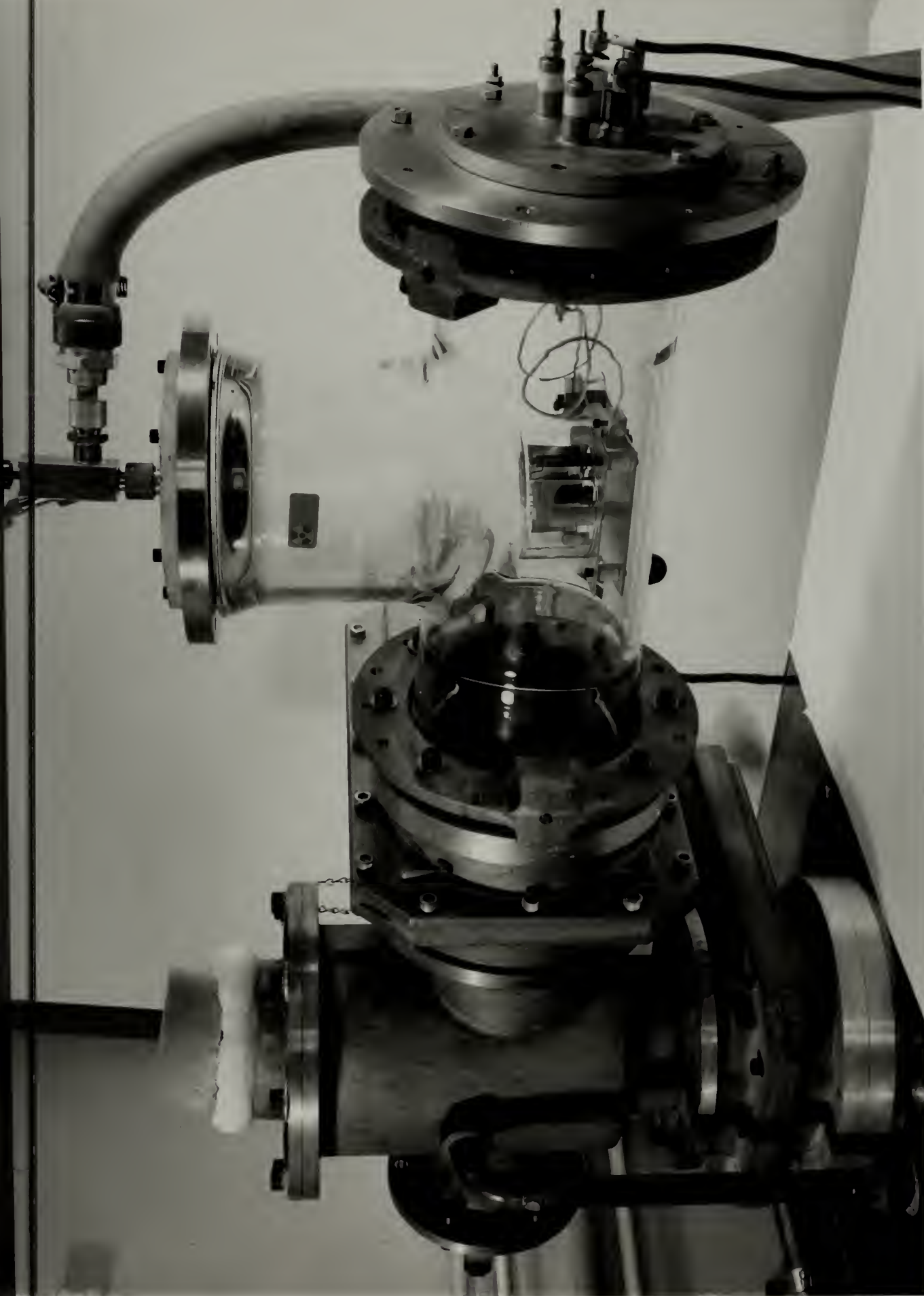


Figure 7 - Vacuum chamber

URL Livermore
Graphic Arts Dept.
Neg. No. 24117

UNCLASSIFIED
WITHOUT QUESTION
NOT FOR PUBLICATION
WITHOUT PERMISSION

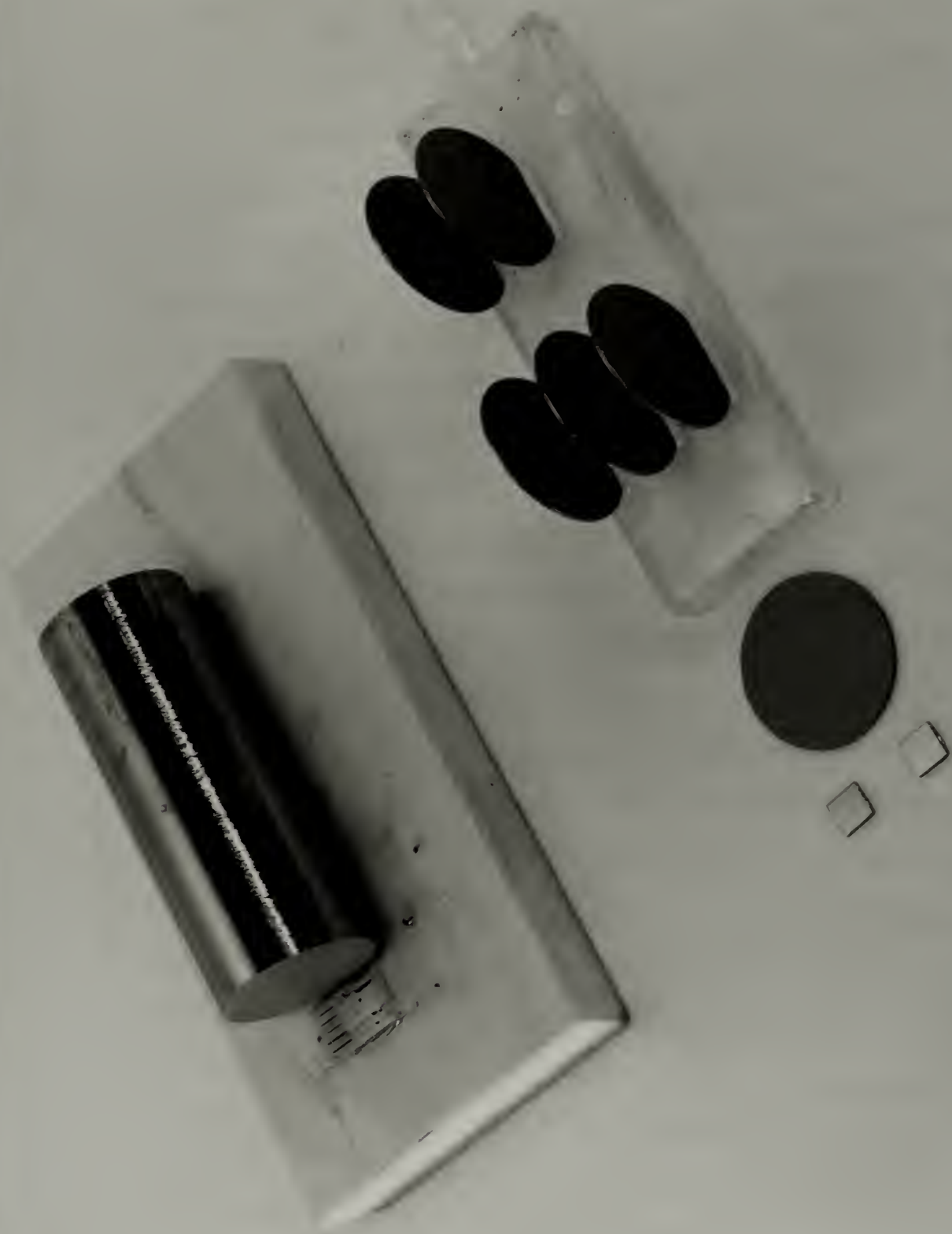


Figure 2 - Si⁺ on single crystal, silicon slices and quartz holder

IRL Livermore
Graphic Arts Dept.
Inv. No. 24113

NOT FOR PUBLICATION
WITHOUT PERMISSION

Figure 10 to be included in UCRL report.

84

1840-1841

1840-1841
1841-1842
1842-1843



Figure 11 - Diffusion furnace

Mr. Livermore
Graphic Arts Dept.
Rec. No. 84/115

UNCLASSIFIED

WITHOUT COMMENT

NOT FOR PUBLICATION
WITHOUT PERMISSION

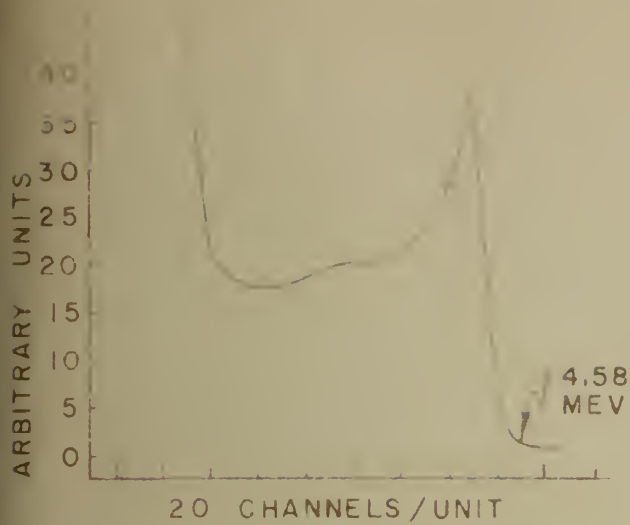


Fig. 12

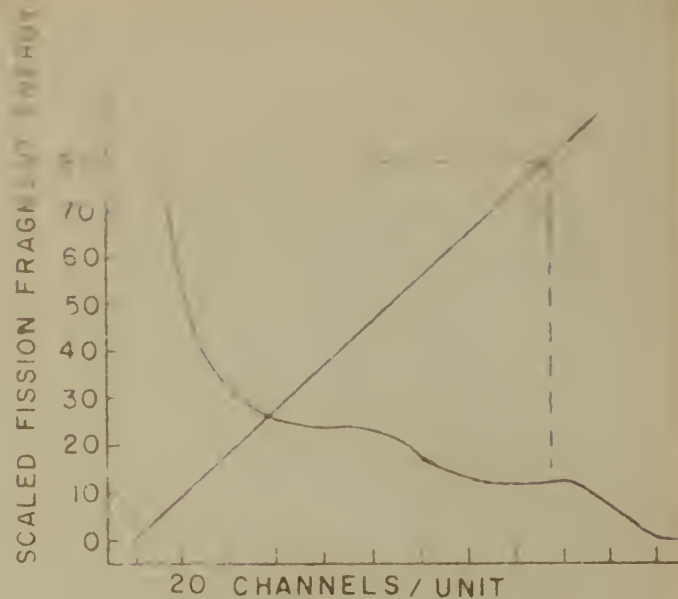
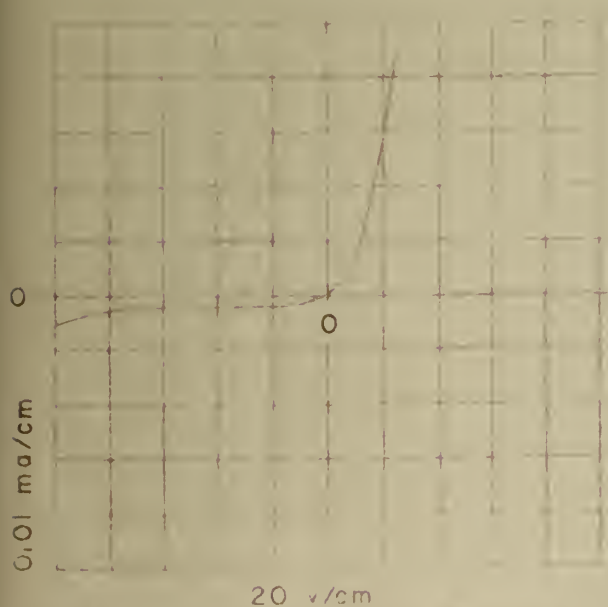
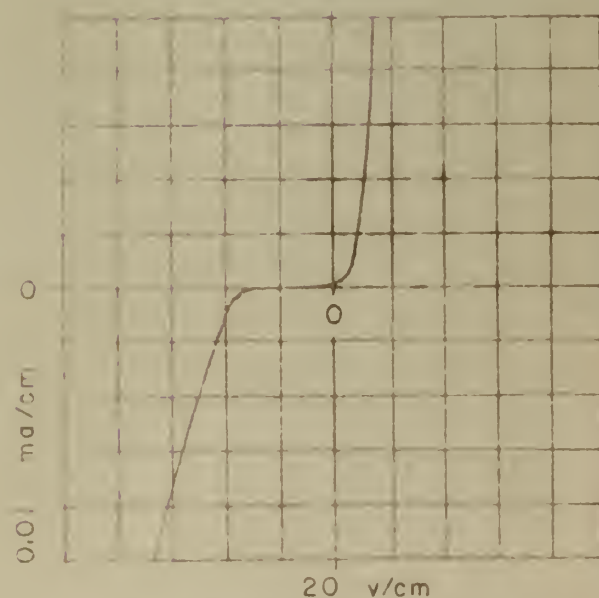


Fig. 13



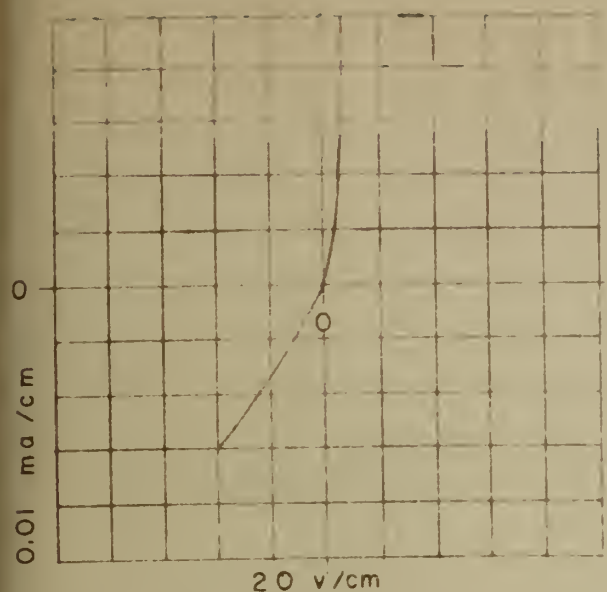
DIODE CHARACTERISTICS OF THE URANIUM COATED, OXIDE SURFACE BARRIER DETECTOR.

Fig. 14



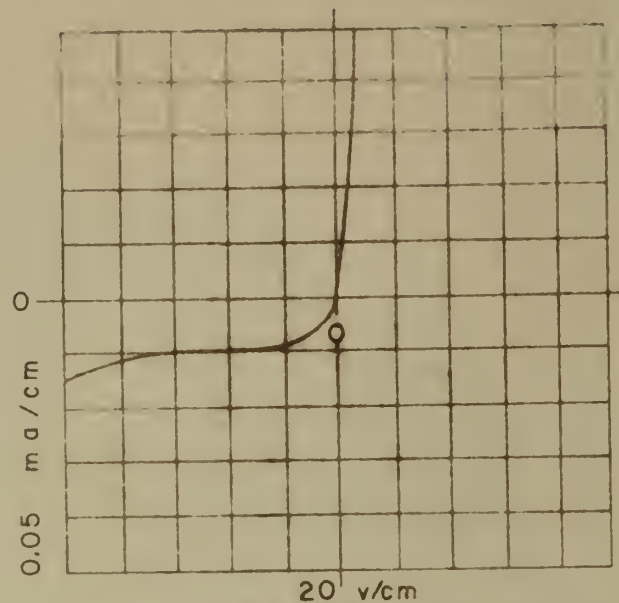
DIODE CHARACTERISTICS OF THE URANIUM COATED, FRESHLY ETCHED SURFACE BARRIER DETECTOR.

Fig. 15



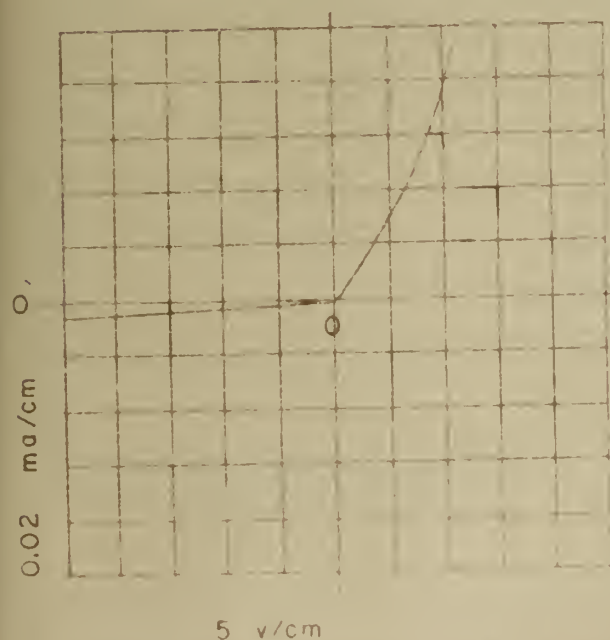
DIODE CHARACTERISTICS OF THE
URANIUM COATED, BORON DIFFUSED
DETECTOR.

Fig. 16



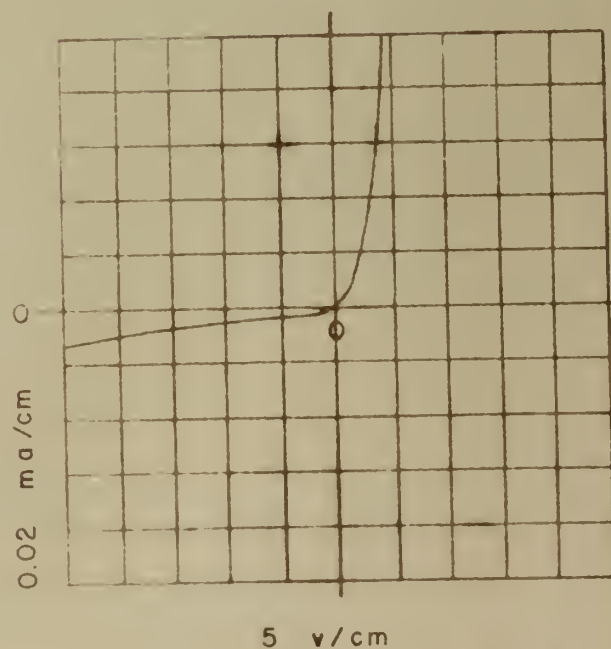
DIODE CHARACTERISTICS OF THE
URANIUM & GOLD COATED SURFACE
BARRIER DETECTOR.

Fig. 17



DIODE CHARACTERISTICS OF A BORON-10
PAINTED, BORON DIFFUSED DETECTOR.

Fig. 18



DIODE CHARACTERISTICS OF A
BORON-10 DIFFUSED DETECTOR.

Fig. 19

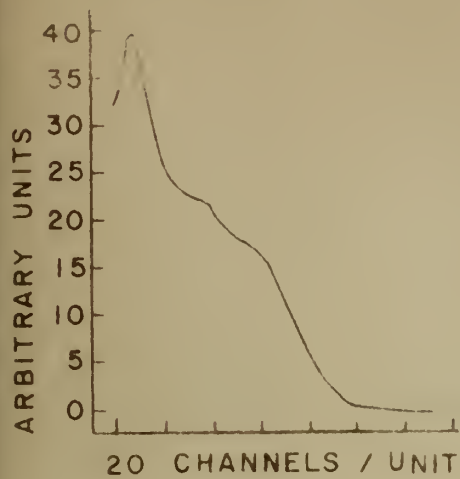


Fig. 20

BORON-10 REACTION PARTICLE SPECTRUM,
0 VOLTS REVERSE BIAS.

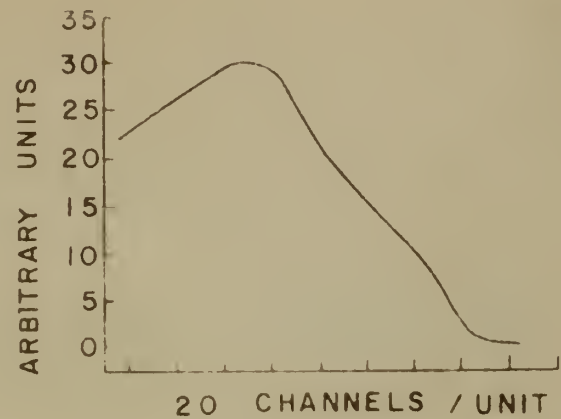


Fig. 21

BORON-10 REACTION PARTICLE SPECTRUM,
5 VOLTS REVERSE BIAS.

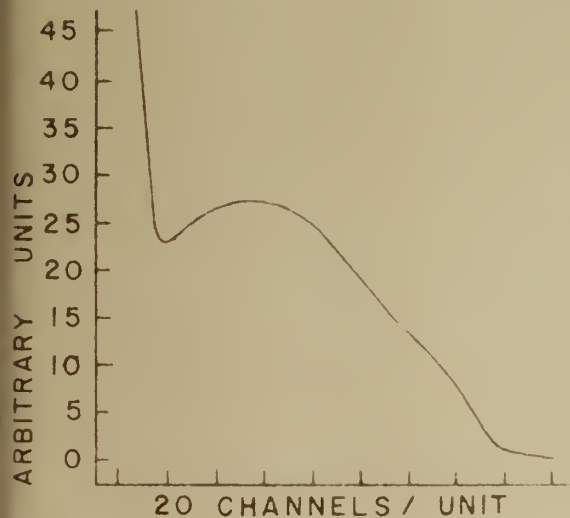
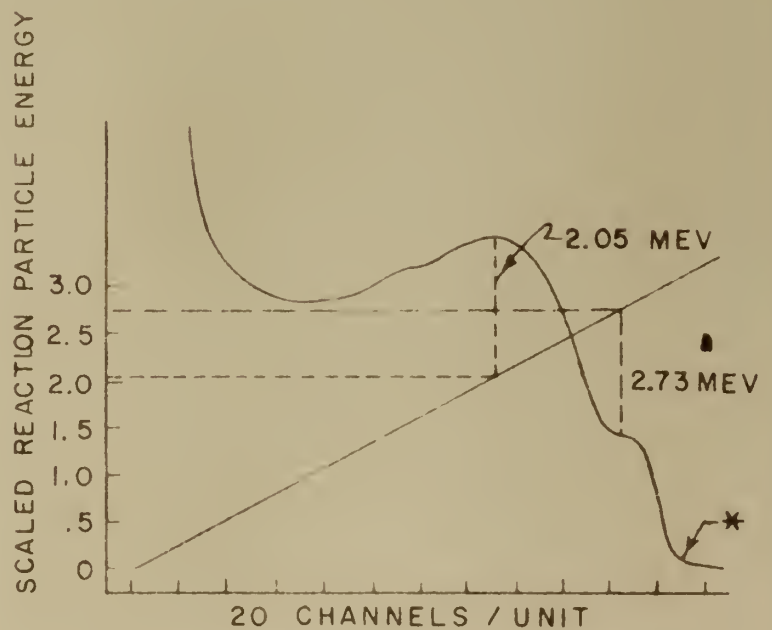


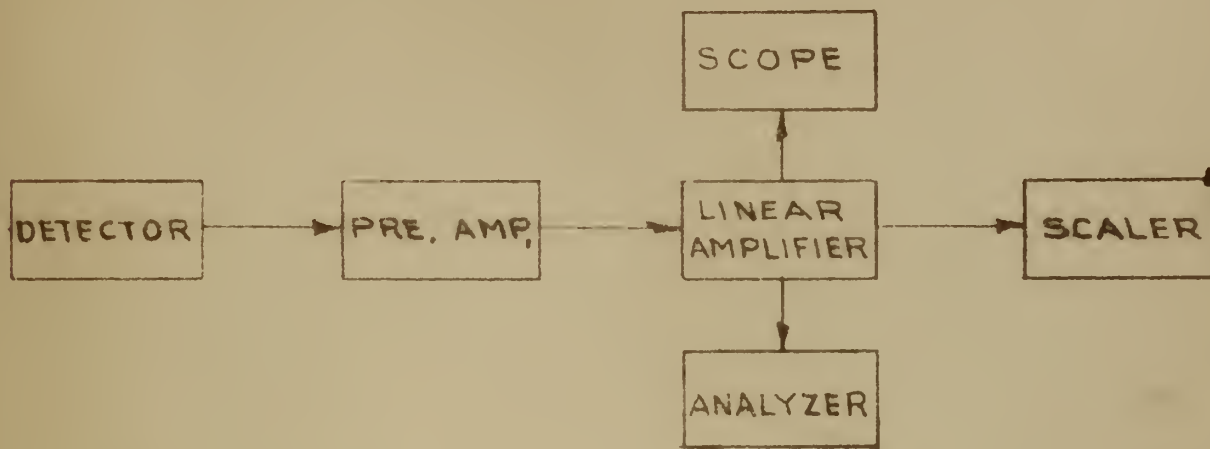
Fig. 22

BORON-10 REACTION PARTICLE SPECTRUM,
10 VOLTS REVERSE BIAS.



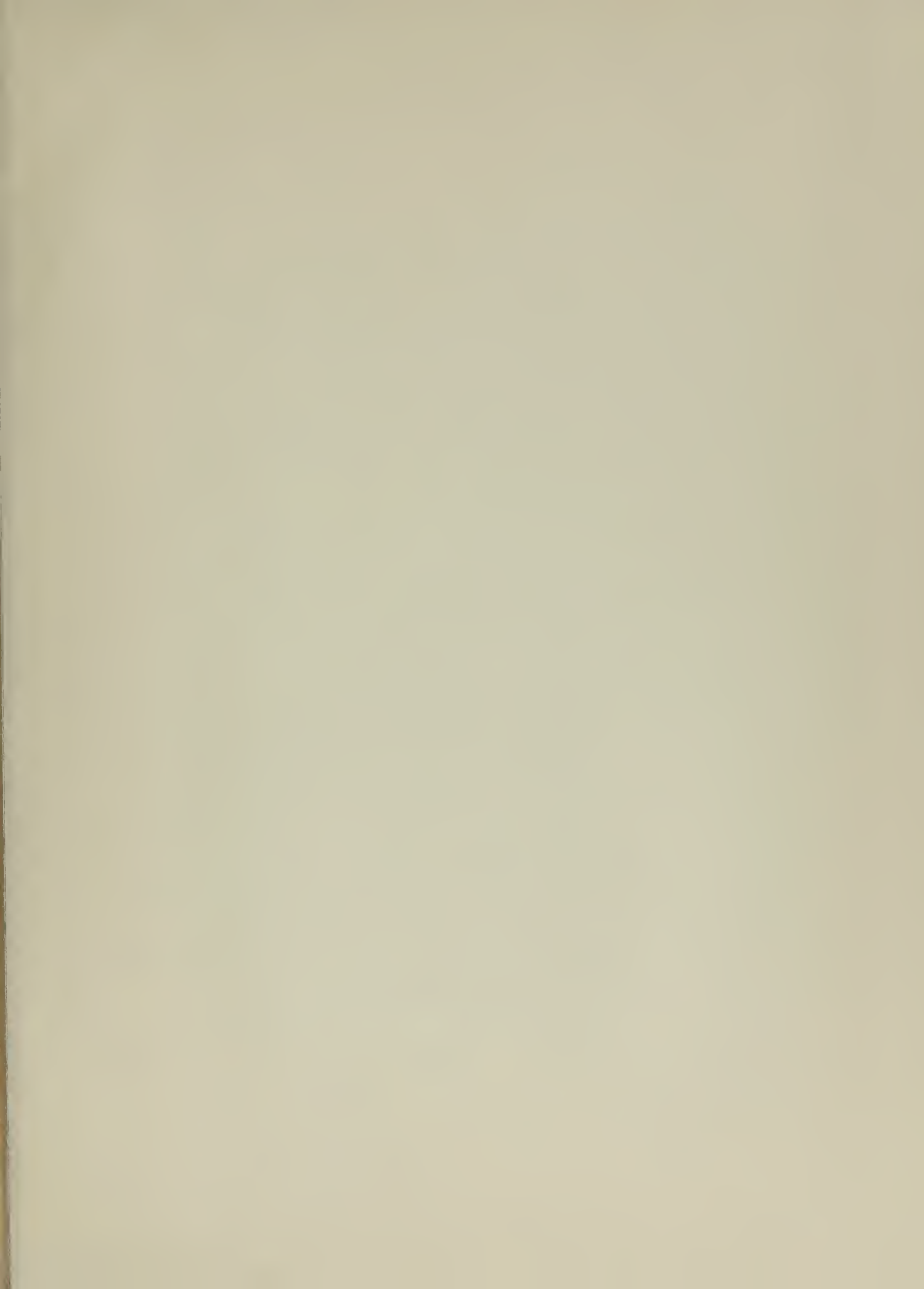
* MAXIMUM ENERGY OF TRITON
Fig. 23

LITHIUM-6 REACTION PARTICLE SPECTRUM,
10 VOLTS REVERSE BIAS.



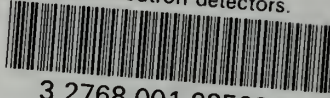
ELECTRONICS TEST EQUIPMENT

Fig. 24



thesM965

Solid state neutron detectors.



3 2768 001 92568 8

DUDLEY KNOX LIBRARY